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*Temporal Variation Characterization
for LMCS Channel
and System Design Implications*

by

Nausheen Naz

*A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of*

Master of Engineering

**Ottawa-Carleton Institute for Electrical and Computer Engineering
Department of Systems and Computer Engineering
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Ottawa, Ontario**

Date of Submission : May 1999

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Graduate Studies and Research acceptance of the thesis

*Temporal Variation Characterization
for LMCS Channel
and System Design Implications*

submitted by Nausheen Naz
in partial fulfillment of the requirements for the
degree of Master of Engineering

Thesis Supervisor

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May, 1999**

Abstract

Local Multipoint Communications Services (LMCS) is a broadband wireless access technology for the provision of multi-media communication services to subscribers at fixed locations. Due to the unavailability of large bandwidth at lower frequency band, these systems will operate in the frequency range of 23 to 40GHz (in North America). The successful operation of point to multipoint system (LMCS/LMDS) at these frequencies necessitates the exact channel characterization. LMCS systems designed with actual channel characteristics will provide high spectral efficiency along with quality of service QoS guarantees comparable to other competitive access technologies (for example, Hybrid Fiber Coaxial, Digital Subscriber Line, Passive Optical Networks).

In this work, we studied the temporal fading characterization at 29.5GHz using narrowband (CW) measurements at 29.5GHz. From the measurements we obtained envelope distributions, statistics of fade rate and fade duration for several radio link environment, including those affected by wind-blown foliage and others affected by moving vehicles acting as scatters and reflectors. Based on these measurement results we studied the performance of adaptive modulation schemes, popular channel coding schemes, requirements for interleavers with and without ARQ (automatic repeat request). several power control algorithms are also suggested. Furthermore, we studied the performance of DAVIC 1.2 physical layer recommendations for G.826 defined parameters.

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Table of Contents

Abstract	iii
Acknowledgement	iv
List of Figures	x
List of Tables	xv

Chapter 1 : Introduction and Problem Statement 1

1.1 Thesis Background	1
1.2 Thesis Objectives and Motivation	2
1.3 Thesis contributions	3
1.4 Thesis Organization	4

Chapter 2 : LMCS System Architecture Issues 6

2.1 Applications and Service requirements	7
2.2 Spectrum Allocation	8
2.3 Cell Architecture	9
2.4 Propagation impairments	11
2.5 Antenna Technology	11
2.6 Equalization	12

2.7 Modulation	12
2.8 Error Control Coding	13
2.9 Power Control	13
2.10 Multiple Access Issues	14

Chapter 3 : Temporal Variation Characterization for Outdoor LMDS Channel 15

3.1 CW Equipment description	17
3.2 Link Budget Analysis	19
3.3 Propagation Measurement	23
3.3.1 Measurements Scenarios	23
3.3.2 Measurement Procedure	24
3.3.3 Observations	26
3.3.3.1 Effects of foliage movements imparted from Wind	26
3.3.3.2 Effects of passing Vehicles	26
3.4 Data Analysis.....	28
3.4.1 Procedure	28
3.4.1.1 Cumulative distribution function of the received signal strength	30
3.4.1.2 AutoCorrelation	30
3.4.1.3 Doppler Power Spectrum (Power Spectral Density)	31
3.4.1.4 CDF of Fading Bandwidth (Doppler Spread)	31
3.4.1.5 Level Crossing Rate	32
3.4.1.6 Fade Duration	32
3.4.1.7 Non-Fade Duration	32
3.4.1.8 Fall and Rise Time of the Fade	33
3.4.2 Results	34
3.4.2.1 Effects of foliage movement because of wind	34
3.4.2.1.1 Location-Power Profile.....	34
3.4.2.1.2 Typical Envelope Fading	37
3.4.2.1.3 Cumulative distribution function of the Received Signal Strength	39
3.4.2.1.4 Autocorrelation Function	41
3.4.2.1.5 Power Spectral Density	44

3.4.2.1.6	Cumulative Distribution Function of Fading Bandwidth (Doppler Spread)	46
3.4.2.1.7	Level Crossing Rate	49
3.4.2.1.8	Fade duration	51
3.4.2.1.9	Fall and rise time of the fade	54
3.4.2.1.10	Non-fade duration	56
3.4.2.2	Effects of passing vehicles	59
3.4.2.2.1	Location-Power Profile	59
3.4.2.2.2	Typical Envelope Fading	62
3.4.2.2.3	Cumulative distribution function of the Received Signal Strength	64
3.4.2.2.4	Autocorrelation Function	66
3.4.2.2.5	Power Spectral Density	68
3.4.2.2.6	Cumulative Distribution Function of Fading Bandwidth (Doppler Spread)	71
3.4.2.2.7	Level Crossing Rate	73
3.4.2.2.8	Fade duration	76
3.4.2.2.9	Fall and rise time of the fade	78
3.4.2.2.10	Non-fade duration	81
3.4.3	Goodness of fit test for fading Signal Envelope	83
3.4.3.1	Procedure	83
3.4.3.2	Goodness of Fit test for the Effects of foliage Movement	91
3.4.3.3	Goodness of Fit test for the Effects of the passing vehicles	93
3.5	Summary of the results	96

Chapter 4 : System Design Implications 98

4.1	Temporal Variation statistics at particular threshold	99
4.2	LMCS System - design and performance Evaluation.....	101
4.2.1	Performance Parameters	101
4.2.2	Power control algorithm	103
4.2.2.1	Assumptions	103
4.2.2.2	Approach 1 (Periodic Power Control)	104
4.2.2.3	Approach 2 (Power Control using Hybrid-ARQ)	107
4.2.2.4	Approach 3 (BER based Power Control)	108

4.2.3	Changing the power Levels	108
4.2.4	Adaptive modulation scheme	109
4.2.5	Forward Error Correction	130
4.2.5.1	Reed Solomon Codes	133
4.2.5.2	Convolutional Codes and RCPC	138
4.2.6	Interleaver	141
4.2.6.1	Performance Parameters for Interleaver	144
4.2.6.1.1	Efficiency	144
4.2.6.1.2	End-to-End Delay	144
4.2.6.1.3	Memory Requirement	145
4.3	Automatic Repeat Request (ARQ)	147
4.3.1	Throughput Estimation	148
4.3.1.1	Assumptions	149
4.3.1.2	Performance Evaluation	151
4.4	Performance Evaluation OF DAVIC 1.2 Recommendations For LMCS	154
4.4.1	Physical Layer Specifications	154
4.4.1.1	Procedure	156
4.4.1.2	Performance Results	159
4.5	Summary of the Results	163

Chapter 5 : Conclusions And Suggestions 165

5.1	Summary of Thesis	165
5.2	Summary of Results	166
5.3	Suggestions for Future Research	168
	References	i

List of Figures

Figure 2.1 :	LMDS Band Allocation (Local Multipoint Distribution Service)	8
Figure 2.2 :	LMCS Cell Structure	9
Figure 3.1 :	CW Transmitter Block Diagram	17
Figure 3.2 :	CW Receiver Block Diagram	18
Figure 3.3 :	Calibration Curve	28
Figure 3.4 :	Fall and Rise Time of the Fade Period	33
Figure 3.5(a) :	Location-Power Profile (Ashley Street in Experimental Farm)	35
Figure 3.5(b) :	Location-Power Profile (MorningSide Street in Experimental Farm)	35
Figure 3.5(c) :	Location-Power Profile (University Drive and Campus Avenue in Carleton University) ..	36
Figure 3.5(d) :	Location-Power Profile (Heron Bridge)	36
Figure 3.6(a) :	Envelope fading with time (Experimental Farm)	38
Figure 3.6(b) :	Envelope fading with time (Carleton University)	38
Figure 3.6(c) :	Envelope fading with time (Heron Bridge)	39
Figure 3.7(a) :	CDF of Envelope Fading (Experimental Farm)	40
Figure 3.7(b) :	CDF of Envelope Fading (Carleton University)	40
Figure 3.7(c) :	CDF of Envelope Fading (Heron Bridge)	41
Figure 3.8(a) :	Time Autocorrelation of Envelope Fading (Experimental Farm)	42

Figure 3.8(b) : CDF of Coherence Time (Experimental Farm)	42
Figure 3.9(a) : Time Autocorrelation of Envelope Fading (Carleton University)	42
Figure 3.9(b) : CDF of Coherence Time (Carleton University)	42
Figure 3.10(a) : Time Autocorrelation of Envelope Fading (Heron Bridge)	43
Figure 3.10(b) : CDF of Coherence Time (Heron Bridge)	43
Figure 3.11(a) : Time Autocorrelation of Envelope Fading for foliage movement	43
Figure 3.11(b) : CDF of Coherence Time Envelope Fading for foliage movement	43
Figure 3.12(a) : Doppler Power Spectrum of Envelope Fading (Experimental Farm)	44
Figure 3.12(b) : Doppler Power Spectrum of Envelope Fading (Carleton University)	45
Figure 3.12(c) : Doppler Power Spectrum of Envelope Fading (Heron Bridge)	45
Figure 3.12(d) : Doppler Power Spectrum of Envelope Fading for foliage movement	46
Figure 3.13(a) : CDF of Fading Bandwidth of Envelope Fading (Experimental Farm)	47
Figure 3.13(b) : CDF of Fading Bandwidth of Envelope Fading (Carleton University)	47
Figure 3.13(c) : CDF of Fading Bandwidth of Envelope Fading (Heron Bridge)	48
Figure 3.13(d) : CDF of fading bandwidth of envelope fading for foliage movement	48
Figure 3.14(a) : Level Crossing Rate (Experimental Farm)	49
Figure 3.14(b) : Level Crossing Rate (Carleton University)	50
Figure 3.14(c) : Level Crossing Rate (Heron Bridge)	50
Figure 3.14(d) : Level Crossing Rate for foliage movement	51
Figure 3.15(a) : Fade duration (Experimental Farm)	52
Figure 3.15(b) : Fade duration (Carleton University)	52
Figure 3.15(c) : Fade duration (Heron Bridge)	53
Figure 3.15(d) : Fade duration for foliage movement	53
Figure 3.16(a) : Fall and Rise time (Experimental Farms)	54
Figure 3.16(b) : Fall and Rise time (Carleton University)	55
Figure 3.16(c) : Fall and Rise time (Heron Bridge)	55
Figure 3.16(d) : Fall and Rise time of the fade (foliage movement)	56
Figure 3.17(a) : Non-fade duration during fading interval (Experimental Farm)	57

Figure 3.17(b) : Non-fade duration during fading interval (Carleton University)	57
Figure 3.17(c) : Non-fade duration during fading interval (Heron Bridge)	58
Figure 3.17(d) : Non-fade duration during fading interval for foliage movement.....	58
Figure 3.18(a) : Location-Power Profile (Bronson Bridge)	60
Figure 3.18(b) : Location-Power Profile (Prince of Wales Drive 1)	60
Figure 3.18(c) : Location-Power Profile (Prince of Wales Drive 2)	61
Figure 3.18(d) : Location-Power Profile (Heron Bridge)	61
Figure 3.19(a) : Envelope fading with time (Bronson Bridge)	62
Figure 3.19(b) : Envelope fading with time (Prince of Wales Drive)	63
Figure 3.19(c) : Envelope fading with time (Heron Bridge)	63
Figure 3.20(a) : CDF of envelope fading (Bronson Bridge)	64
Figure 3.20(b) : CDF of envelope fading (Prince Of Wales Drive)	65
Figure 3.20(c) : CDF of envelope fading (Heron Bridge)	65
Figure 3.21(a) : Time Autocorrelation of Envelope Fading (Bronson Bridge)	66
Figure 3.21(b) : CDF of Coherence Time (Bronson Bridge)	66
Figure 3.22(a) : Time Autocorrelation of Envelope Fading (Prince of Wales Drive)	67
Figure 3.22(b) : CDF of Coherence Time (Prince of Wales Drive)	67
Figure 3.23(a) : Time Autocorrelation of Envelope Fading (Heron Bridge)	67
Figure 3.23(b) : CDF of Coherence Time (Heron Bridge)	67
Figure 3.24(a) : Time Autocorrelation of Envelope Fading for passing vehicles	68
Figure 3.24(b) : CDF of Coherence Time for passing vehicles	68
Figure 3.25(a) : Doppler power spectrum of envelope fading (Bronson Bridge)	69
Figure 3.25(b) : Doppler power spectrum of envelope fading (Prince of Wales Drive)	69
Figure 3.25(c) : Doppler power spectrum of envelope fading (Heron Bridge)	70
Figure 3.25(d) : Doppler power spectrum of envelope fading for passing vehicles	70
Figure 3.26(a) : CDF of fading bandwidth of envelope fading (Bronson Bridge)	71
Figure 3.26(b) : CDF of fading bandwidth of envelope fading (Prince of Wales Drive).....	72
Figure 3.26(c) : CDF of fading bandwidth of envelope fading (Heron Bridge)	72

Figure 3.26(d)	: CDF of fading bandwidth of envelope fading for passing vehicles	73
Figure 3.27(a)	: Level Crossing Rate (Bronson Bridge)	74
Figure 3.27(b)	: Level Crossing Rate (Prince of Wales Drive)	74
Figure 3.27(c)	: Level Crossing Rate (Heron Bridge)	75
Figure 3.27(d)	: Level Crossing Rate for passing vehicles	75
Figure 3.28(a)	: Fade duration (Bronson Bridge)	76
Figure 3.28(b)	: Fade duration (Prince of Wales Drive)	77
Figure 3.28(c)	: Fade duration (Heron Bridge)	77
Figure 3.28(d)	: Fade duration for passing vehicles	78
Figure 3.29(a)	: Fall and Rise time (Bronson Bridge)	79
Figure 3.29(b)	: Fall and Rise time (Prince Of Wales Drive)	79
Figure 3.29(c)	: Fall and Rise time (Heron Bridge)	80
Figure 3.29(d)	: Fall and Rise time of the fade (Passing vehicles)	80
Figure 3.30(a)	: Non-fade duration during fading interval (Bronson Bridge)	81
Figure 3.30(b)	: Non-fade duration during fading interval (Prince of Wales Drive)	82
Figure 3.30(c)	: Non-fade duration during fading interval (Heron Bridge)	82
Figure 3.30(d)	: Non-fade duration during fading interval for passing vehicles	83
Figure 4.1	: Scanning overhead of power control command at different link margin.	106
Figure 4.2	: Probability of bit error for PSK signals.....	113
Figure 4.3	: Adaptive modulation of PSK scheme	113
Figure 4.4	: Case -1: Adaptive modulation of PSK scheme for increase in maximum constellation size with increase in link margin.....	117
Figure 4.5	: (a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of M-PSK at different link margin (case 1)	118
Figure 4.6	: Case -2: Adaptive modulation of PSK scheme for decrease in maximum constellation size with increase in link margin	119

Figure 4.7 :	(a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of M-PSK at different link margin (case 2)	120
Figure 4.8 :	Case -3: Adaptive modulation of PSK scheme for same maximum constellation size with increase in link margin	121
Figure 4.9 :	Probability of bit error for QAM signals	124
Figure 4.10 :	Adaptive modulation of QAM scheme	125
Figure 4.11 :	(a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of rectangular M-QAM at different link margin (Case 1)	128
Figure 4.12 :	(a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of rectangular M-QAM at different link margin (Case 2)	129
Figure 4.13 :	(a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of rectangular M-QAM at different link margin (Case 3)	129
Figure 4.14 :	Performance of the RS Code for different Error Correcting Capabilities.....	135
Figure 4.15 :	Performance of RS-code at different link margin.....	138
Figure 4.16 :	Performance of Punctured Convolutional codes at different link margin.....	140
Figure 4.17 :	Randomization Efficiency of the Interleaver	146
Figure 4.18 :	End-to-end Delay of the Interleaver	146
Figure 4.19 :	Link utilization of the ARQ Schemes for Burst Errors	153
Figure 4.20 :	Probability Density Function of Received Signal Strength	157
Figure 4.21 :	BER performance for DAVIC downstream Scenario 1	159
Figure 4.22 :	ESR performance for DAVIC downstream Scenario 1	160
Figure 4.23 :	BER performance for DAVIC downstream Scenario 2	160
Figure 4.24 :	ESR performance for DAVIC downstream Scenario 2	161
Figure 4.25 :	BER performance for DAVIC upstream	161
Figure 4.26 :	ESR performance for DAVIC upstream	162

List of Tables

Table 3.1:	Link Budget of CW equipment for different distances.....	22
Table 3.2:	Summary of Propagation Measurements	24
Table 3.3:	Summary of Goodness of fit test for foliage movement.....	92
Table 3.4:	Summary of Goodness of fit test for passing vehicles.....	95
Table 4.1:	99th percentile of temporal variation statistics	100
Table 4.2:	Fade duration in bytes at different data rates	135

Chapter 1

Introduction and Problem Statement

1.1 THESIS BACKGROUND

Research in Local Multi-point Communication System (LMCS) or Local Multipoint Distribution System (LMDS) technology started in early 1990's and major issues related to system engineering have already been dealt with [12],[14]-[18],[35]-[38]. Early research findings proved very promising, and hence resulted in the competitive auction of LMDS bands in the US and LMCS band awards in Canada. However, some issues of LMCS need further study to improve the system performance.

LMCS / LMDS networks are aimed at providing a full range of services including broadband multimedia applications with wired equivalent quality of service (QoS). This requires that the access media to the LMCS/LMDS base stations should be transparent to the end-user (i.e the bit error probabilities is similar to wired media). For this reason, propagation issues play a significant role in the optimum system design. In this thesis we characterize the temporal variation of received signals first and then discuss some digital communication systems issues on the basis of the obtained results.

1.2 THESIS OBJECTIVES AND MOTIVATIONS

The proposed LMCS/LMDS system is generally designed with the optimistic assumption of having perfect LOS (line of sight) radio links. This assumption may be justified for most of the cases in the first generation LMCS/LMDS implementation, where they are targeted at business customers. However for residential areas, there are good chances of having trees or moving vehicles acting as reflectors in between the transmitter and receiver. Also in downtown areas which are very crowded, business subscribers may suffer from degraded service. In order to provide LMCS/LMDS service at every location with the same quality of service, we need to devise some sophisticated and practical digital communication system functions.

Our motivation for this thesis is rooted in the following problems;

- The second and third generation LMCS systems aim to cater to residential as well as business subscribers with multimedia service facilities. The deployment in some places may not have LOS, which can degrade the service quality.
- Foliage and passing vehicles can obstruct LOS links, which may degrade services requirements.
- In the absence of LOS, what measures are needed to comply with G.826 recommendations [34]. It describes the Error Performance Objectives (EPO) required for digital communications systems to support B-ISDN services.

1.3 THESIS CONTRIBUTIONS

In this thesis we focus on the channel characterization relevant to design of error control coding for LMC/LMDS systems. In this respect we study the temporal variations of outdoor channel at 29.5GHz for narrow band signalling. With the help of these measurements we analyzed the candidate modulation and coding schemes. G.826 recommendations [34] have also been analyzed for modulation and coding schemes.

Our major contributions are as follows;

- Temporal Variations characterization for outdoor channel using Continuous Wave (CW) equipment.
- Performance analysis of adaptive constellation size of the modulation schemes based on the measurements results.
- Design and performance evaluation of well known channel codes.
- Performance evaluation of DAVIC [11] proposed modulation and coding schemes for G.826 Error Performance Objectives (EPO) [34].
- Studied power control algorithms for LMCS.
- Studied the impact of interleaver and hybrid ARQ schemes on LMCS system.

Since no detail results on temporal variations characterization at 30GHz band is available in the literature, therefore the work is significant contribution. These results will help to determine the requirements of FEC, interleaver and ARQ schemes. They will also be used to design

adaptive modulation and power control schemes. Furthermore, we have studied the performance of only LMCS specific physical layer recommendations for G.826 EPOs.

1.4 THESIS ORGANIZATION

The thesis is organized into three parts. Part 1 deals with introduction to LMCS systems. This includes chapter 1 and chapter 2. In part 2 we discuss the characterization of time varying statistics of the LMCS/LMDS channel. Part 3 deals with the performance and requirement of modulation schemes, power controls algorithms, channel coding interleavers and hybrid ARQ.

Chapter wise organization of the thesis is as follows.

This chapter (i.e Chapter 1) describes the problem statements and thesis contributions.

Chapter 2 discusses some research issues of LMCS, for example cell and antenna structure, equalization, medium access protocols, modulation and error control coding schemes.

Characterization of LMCS/LMDS outdoor channel for temporal variation statistics are presented in chapter 3. The characterization is done for two scenarios i.e., foliage and moving vehicles. The Kolmogrov-Smirnov test [52] is also performed to find the closeness-of-fit of the distribution of acquired data with the popular channel model on log scale [49].

The reported results in chapter 3 are used to design adaptive modulation schemes, forward error correction, power control algorithms, interleaver and automatic repeat request (ARQ) schemes for LMCS. The performance of these system blocks are also studied. The perfor-

mance of DAVIC1-2 physical layer recommendations is also examined for G.826 EPOs.

Finally, in chapter 5 summary of the results, conclusion based on these results are given. It also includes few scenarios for further research.

Chapter 2

LMCS System Architecture Issues

During the last decade the arrival of the internet and other entertainment services have revolutionized the information world. For a widespread use of these services the computer industry brought high computational power to desk top computers. However, the telecommunication industry is still working on various technologies to provide high speed information highways for access to these services from home and offices. A few important broadband access technologies being evolved include: Digital Subscriber Line (xDSL), Hybrid Fiber Coax (HFC), Passive Optical Networks (PONs) and Local Multipoint Communication Services (LMCS). Widespread deployment of the cable network and the broadband nature of this medium attracted the attention of the telecommunication industry as a possible solution for broadband access. However, ease-and-speed of deployment, fast realization of revenues, mobility capabilities are the salient characteristics of wireless medium. The saturation of radio resources at lower frequency bands and the large bandwidth requirement for broadband applications motivated researchers to investigate the possibilities of utilizing the frequency band in 20-40 GHz.

Local Multipoint Communication Services (LMCS) is a broadband wireless access technology

for multimedia applications at 28GHz to residential and business customers at fixed locations. With a wide experience of the cellular communication and the research in the 28 GHz range, researchers have designed the first generation LMCS system. In this chapter, a service architecture and few of the major research developments are discussed.

2.1 APPLICATIONS AND SERVICE REQUIREMENTS

It is generally believed that first generation LMCS networks are targeted to provide high bandwidth data connection and telephony services to commercial subscribers. Nevertheless, in order to achieve a reasonable market penetration LMCS networks should be able to provide all key applications as offered by competitive access technologies (for example, Hybrid-fibre coax, XDSL, Passive Optical Networks). Some of the popular services include;

- Broadband Internet
- Telephony (Pots)
- File Transfer
- Video conference
- Video on demand

The service requirement varies among different applications. For example call blocking probability, delay, jitter, call setup time are the important service parameters for telephony, whereas cell loss ratio, throughput are key parameters for data traffic.

2.2 SPECTRUM ALLOCATION [37][12]

In the US, the Federal Communications Commission (FCC) set aside two blocks of bandwidth for LMDS as described in [12]. (Block A has a total bandwidth of 1150MHz: 27.5 to 28.35 GHz, 29.1 to 29.25 GHz, 31.075 to 31.225 GHz and block B has a total bandwidth of 150MHz: 31 to 31.075 GHz and 31.225 to 31.35GHz). In Canada, LMCS services in the 27.35 to 28.35 GHz range have been granted to three companies that are now in the process of deploying networks. Four other blocks of 500 MHz have been reserved for future use.

Figure 3-1: LMDS Band Allocation (Local Multipoint Distribution Service) [37]

2.3 CELL ARCHITECTURE

The LMCS system uses the conventional cellular architecture with a frequency reuse factor of 1 and a maximum radius of approximately 5 km. All communication is done through the base-station, which is located at the center of the cell. In order to provide good coverage, overlapping cells are suggested so that most customers would have LOS communication with the base-station. For increased capacity and reduced interference sectorized antennas at the base-stations and highly directive antenna at the customer locations would be used.

Figure 3-2: *LMCS Cell Structure*

A representative LMCS network architecture consists of the following entities:

- Base-Station Equipment
- Customer Premises Equipment
- Network Management Equipment

There may be two possible strategies for the base-station: no-switching and switching options. In case of no-switching at base-station, it will consist of radio-frequency equipment, modem and network interface equipment. The base-station receives data from the customers and transfers it to the network (PSTN, ATM backbone) and vice versa. While in the latter case, the base-station is also responsible for the switching of the data received from the customers and the network.

The customer premises equipment consists of the radio-frequency equipment, modem, service interface cards (for example, Ethernet and Voice).

The network management system is responsible for managing the whole (or a sub-network) from one location. Its main functions include operations, administration and maintenance.

2.4 PROPAGATION IMPAIRMENTS

The LMCS systems uses frequencies in the range of 28 GHz. The major propagation issues at these frequencies are rain attenuation and shadowing because of foliage, buildings and passing vehicles. With more detailed statistics available of the rain fall this problem can be mitigated considerably through higher the link margins.

The issues related to moving foliage and passing vehicles are the subject of this study. The result shows that service requirements can be achieved with reasonable system design (as discussed in chapter 4).

Multipath is not necessarily a dominant issue for LMCS because of LOS link, antenna height, fixed-location of customer and highly directional antennas.

Propagation issues under current investigation are characterization of rain-drop attenuation, cross-polarization discrimination, passive intermodulation effects, characterization of temporal variation of wideband signal, characterization of multipaths and shadowing, and angular distribution of received power.

2.5 ANTENNA TECHNOLOGY

To increase the system capacity and to offer true broadband access, the full system allocated bandwidth can be reused in each cell. This will be a potential cause of interference, which can be reduced considerably through the use of highly directional subscriber antennas and different polarizations in different cells. The use of such antennas is practical because of the fixed wire-

less links. System performance for both downlink and uplink with a reuse factor of 1 is greatly improved through the use of highly directional antennas (refer. to [36]).

Therefore, in order to provide good isolation, the receiving antennas must have high gain, narrow beamwidth and good polarization. The research to develop low cost electronics for such antennas is currently in progress.

2.6 EQUALIZATION

In order to investigate and reduce the effects of inter-symbol interference in LMCS systems research was done to find the equalization requirements at various symbol rates. It was observed that the 90th percentile of multipath delay spread at 29.5 GHz was found to be on the order of 80 nsec. Hence equalization may not be required for the transmission rates of less than 10 Msps. However, we may need equalization with few taps for data rates greater than 25 Msps ([37]). Because of the simplicity of the decision feedback, it appears to be an obvious choice for LMCS systems.

2.7 MODULATION

M-PSK and M-QAM are the candidate modulation schemes for the first generation LMCS systems because of their good spectral efficiency, BER performance and hardware availability.

OFDM (Orthogonal frequency division multiplex) may be used in future generations LMCS systems because of its spectral efficiency and anti-multipath characteristics. However these modulation schemes are sensitive to the non-linear distortions of the transmitter amplifier.

2.8 ERROR CONTROL CODING

In order to guarantee reliable and efficient communication on wireless medium the use of error control coding is recommended. Error control coding is a prime candidate for mitigation of fading in LMCS systems that results from movement of reflectors, scatterers and attenuators in the vicinity of LMCS transmitters and receivers. ARQ schemes provide reliable communications at the cost of low link utilization and access delay (especially for wireless medium). Similarly, at high data rates (or broadband systems) the use of interleaver results in impractical memory requirements and unacceptable delay even for small burst durations. Hence, the use of concatenated codes has been suggested in the DAVIC 1.2 Recommendations and by other researchers of LMCS system. This will provide the low bit error rates at which the ARQ techniques would be used for reliable communications.

For efficient use of radio resources only the optimum amount of coding should be used. This would ensure the reliability of the communication link without wasting link capacity.

In this work, we have studied the optimum coding requirements, interleaving and ARQ scheme based on the characterization of the temporal variations at 29.5 GHz.

2.9 POWER CONTROL

Power control mechanism, are commonly used in CDMA system to mitigate the near-far effect. In LMCS power control algorithms can be used to reduce the effect of temporal fading. In DAVIC1-2 recommendations adaptation of signal level is suggested to improve the link performance. Adaptation of signal constellation can also be used through the help of power con-

trol algorithm. For efficient power control algorithm in order to mitigate temporal variations, fade time should be long enough to process the algorithm. Therefore, fading statistics should be available to design power control schemes. In later chapters we suggest some power control algorithm based on measurement results.

2.10 MULTIPLE ACCESS ISSUES

LMCS system provides bi-directional communication services. A Time Division Multiplex (TDM) scheme will be used in the downstream.

However, the upstream will either use Frequency Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA) based on the nature of the customer's traffic. FDMA is suitable for data rates higher than T1/E1 and requires dedicated use of the channel. TDMA is more appropriate for small and medium size customers with data rates in the order of partial T1/E1. A few important candidate multiple access protocols based on TDMA schemes are DAVIC 1.2[11] MAC Recommendations (LMCS-Specific), IEEE 802.14[58] MAC Convergence draft (HFC-Specific) and Data Over Cable Service Interface Specifications (DOCSIS)[59] MAC Standard (HFC-Specific). Recent research[38] studies shows that both IEEE 802.14 and DOCSIS MAC protocols provides comparable capacity for ATM traffic and are better than the DAVIC MAC protocol.

Chapter 3

Temporal Variation Characterization for Outdoor LMCS Channel

The wireless medium is comparatively more noisy and variable than other communications medium. Furthermore, different bands of frequency behave differently which necessitates the characterization of a particular spectrum being contemplated. LMCS (Local Multipoint Communication Services) is a broadband fixed wireless access system at 29.5 GHz and will provide multimedia services with QoS assurance. Design of a reliable LMCS system architecture requires characterization of outdoor channel at 29.5 GHz. Most of the interesting system architecture issues in this respect have already been studied as discussed in chapter 2. However temporal variations characterization for the LMCS channel has not yet been studied in detail. This study will help to figure out the requirement of coding schemes, modulation schemes, interleaver and ARQ schemes for LMCS/LMDS systems.

A channel is usually characterized using wideband equipment for its impulse response characteristics, and narrowband equipment for its temporal variations characteristics. However, temporal variations of the channel can be characterized using both narrowband and wideband propagation measurements equipment. The wideband equipment for temporal variation char-

acterization at LMCS frequency is currently under development at CRC. The narrowband equipment was used for the temporal variation characterization at LMCS frequency, because of the availability of the equipment.

The effect of multipath fading is generally more severe for narrowband signals than for wideband or broadband signals. This is possibly due to the vector addition of narrowband signals from multipath while it is the algebraic addition of the wideband and broadband signals from multipath. This means that narrowband system generally exhibit worse channel variations than do or broadband system. However, the effect of time varying shadowing is similar for all bands. It should also be noted that, the effect of multipath is not very significant for LOS systems (for example, LMCS) with highly directive antennas.

In order to characterize the channel for temporal variations, propagation measurements were carried out using CW (Continuous Wave) equipment at 29.5GHz in and around the Carleton University during summer and fall of 1998. Statistical analysis of the CW data is then done using the procedure described in section 3.4 of this chapter [16].

This chapter describes the CW equipment, data acquisition software-and-hardware and the link budget of the equipment used for propagation measurement. Propagation measurements procedure, scenarios and some of the observations during field measurement is explained in section 3.3. The procedure for data analysis and the results for separate scenarios is described in section 3.4. Finally the last section concludes the results obtained.

3.1 CW EQUIPMENT DESCRIPTION

CW equipment was designed and built by Robert B. Hahn, in a joint project between CRC and Carleton University. Detailed specification and description of the equipment can be found in [14]. Following is a brief description of the equipment.

CW measurement equipment consists of four basic units: Transmitter, Receiver, Battery, Portable Personal Computer (Laptop).

The transmitter unit consists of two linear polarized 29.5 GHz Gunn oscillators. One of its outputs is horizontally polarized while the other is vertically polarized. Flann canonical horn antennas with gain of 28dBi and beam-width of (6.2 ± 3.1) degrees are used for transmission of the CW signal. Figure 3.1 shows the schematic diagram of the transmitter unit. The warm-up period for the transmitter is about 30 minutes. It is mounted on a tripod stand and is driven by 110Volts power source (for details please refer to [14]).

Figure 3-1: CW Transmitter Block Diagram[14]

The Receiver unit is a double conversion system with two voltage controlled oscillators. Both manual tuning and computer aided tuning through a PCMCIA card are available in the equipment. A Flann canonical horn antenna with azimuthal beam width of 6.2 degrees and antenna gain of 28dBi is used. Two analog meters on the receiver's panel show amplitude and frequency drift of the signal. The amplitude of the signal and frequency drift can be acquired and saved on the disk of portable computer through a PCMCIA based DAQ (Data Acquisition) card. The receiver units can be powered through a chargeable battery with 10-17V and 1A current.

Figure 3-2: CW Receiver Block Diagram [14]

The bandwidth of the equipment is 4MHz with IF frequency at 160MHz. The dynamic range of the equipment is 60dB without the antenna.

A 160 Mhz pentium laptop computer with PCMCIA based Data Acquisition card and Lab-View software is used to acquire the data into the computer. The DAQ card has a 12-bit analog to digital converter and can support the maximum sampling rate of 100 kilo samples per second. The sampling rate of 2k samples/sec was used for all acquisitions. Labview software is used to acquire data and MATLAB is used for data analysis.

3.2 LINK BUDGET ANALYSIS

The link budget of the CW equipment used are as follows.

The effective isotropic radiated power is defined as;

$$EIRP = P_t + G_t \quad \text{Eq (3.1)}$$

where P_t = RF output power of the transmitter (dBm)

G_t = Transmitting antenna gain (dBi)

For the CW equipment used in propagation measurement $P_t = 20dBm$ and $G_t = 27dBi$, therefore the EIRP of the equipment is;

$$EIRP = 47dBm \quad \text{Eq (3.2)}$$

Free Space Loss (FSL) at distance D is given as;

$$FSL_{dB} = 32.44 + 20\log D + 20\log f \quad \text{Eq (3.3)}$$

where D = distance between TX and RX antennas in kilometers

f = frequency in Megahertz

Free space loss for a distance of 1km between transmitter and receiver at the frequency of 29.5GHz (29497MHz) is calculated as;

$$FSL_{dB} = 122dB \quad \text{Eq (3.4)}$$

The Isotropic Receive Level (IRL) of the given equipment can be calculated as follows;

$$IRL = EIRP - FSL \quad \text{Eq (3.5)}$$

$$IRL = -75dBm \quad \text{Eq (3.6)}$$

Received Signal Level (RSL) at 1km for the given equipment is given as;

$$RSL = IRL + G_r - \text{line loss} \quad \text{Eq (3.7)}$$

where G_r = Receiving Antenna gain = 27dBi and $\text{line loss} = 6\text{dB}$

$$RSL = -54\text{dBm} \quad \text{Eq (3.8)}$$

Noise Floor (NF) of the equipment is defined as;

$$NF = -174\text{dBm} + \text{Noise figure} + 10\log(\text{IF bandwidth}_{\text{Hz}}) \quad \text{Eq (3.9)}$$

A $\text{Noise Figure} = 2\text{dB}$ can be assumed to calculate the Noise Floor of the equipment. The IF bandwidth of the equipment is 4MHz, therefore noise floor of the equipment is;

$$NF = -108\text{dBm} \quad \text{Eq (3.10)}$$

Signal to noise ratio (SNR) of the equipment is an important parameter. It tells the ability of the equipment to detect the signal, in the presence of the noise. It is defined as;

$$SNR = RSL_{\text{dBm}} - NF_{\text{dBm}} \quad \text{Eq (3.11)}$$

For the given equipment, with a range of 1km;

$$SNR = 54\text{dB} \quad \text{Eq (3.12)}$$

Now Fade Margin of the equipment at 1km can be calculated as;

$$\text{FadeMargin} = \text{SNR} - 10\text{dB} \quad \text{Eq (3.13)}$$

$$\text{FadeMargin} = 44\text{dB} \quad \text{Eq (3.14)}$$

The link budget for 1.5, 2, 25 and 3 km. is shown in Table 3.1.

Link Budget	Distances				
	1km	1.5km	2km	2.5km	3km
EIRP (dBm)	47				
FSL (dB)	122	126	128	130	132
IRL(dBm)	-75	-79	-81	-83	-85
RSL(dBm)	-54	-58	-60	-62	-64
NF(dBm)	-108				
SNR (dB)	54	50	48	46	44
Fade Margin (dB)	44	40	38	36	34

Table 3.1: Link Budget of CW equipment for different distances

3.3 PROPAGATION MEASUREMENT

3.3.1 Measurements Scenarios

As we discussed earlier, first phase of LMDS/LMCS deployment will usually work on LOS links. Though the effect of temporal variation on the LOS link performance will not be significant, it can still occur due to one or more reflected rays added to the LOS ray. In second generation LMDS/LMCS systems one may or may not have LOS links because of trees or passing vehicles between the transmitting and receiving antennas, in some areas. Considering all these facts the following two scenarios have been observed and analyzed in detail:

- Temporal variations because of foliage movements due to wind.
- Temporal variations because of passing vehicles.

Altogether 250 links were observed, each for the duration of 10 minutes. Out of 250 links, 115 links were established for observing the effect of leaf movement (because of wind) on the signal. And 113 links were observed for the effect of passing vehicles. In addition to these 22 links were observed on Billings Bridge for the general effect of both passing vehicles and foliage movements caused by wind. A summary of all these links is given in table 3.2.

Measurement were taken in the Experimental Farm, Carleton University (near university residences, railway crossing), Heron Bridge, Bronson Bridge and Prince of Wales Drive.

While observing the effects of leaf movement, care has been taken to avoid vehicles crossing the receiving antenna (though in a few cases buses could not be avoided). Similarly, trees were avoided while observing the effect of passing vehicles.

3.3.2 Measurement Procedure

Propagation measurements were taken at six different places around Carleton University. Table 3.2 below gives an overview of all observed links at these places.

S.No.	Location	Approx. Distance b/w Tx & RX. Antenna	No. of links observed	Dominant Object
1.	Experimental Farm	700m 1.7km	56	trees
2.	Prince Of Wales Drive	700m	69	vehicles
3.	Billings Bridge	1.7km	22	both
4.	Bronson Bridge	700m	27	vehicles
5.	Heron_1	500m	7	trees
6.	Heron_2	600m	17	vehicles
7.	Carleton University (Campus Avenue and University Drive)	200m	52	trees

Table 3.2: Summary of Propagation Measurements

At each place several links were established and data was recorded in the laptop at each of these links for 10 minutes at the sampling rate of 2K samples per second. During the data logging, the receiver was kept stationary. After 10 minutes, when the data logging stopped, a new link was established by moving the receiver within 30-50m of the previous location, so that the observations could be made not only for different types of trees but also at different distances from the trees or vehicles.

Since neither trees nor vehicles are able to move faster than 1kHz, a sampling rate of 2000

samples per second is fast enough to observe the variation because of leaf movement due to wind and passing vehicles. This has also been verified by visualizing some preliminary measurements recorded for 5k samples/sec and 10k samples/sec. Acquisitions are saved in a binary file as they require less memory and expedite data acquisition. After acquisition these files are converted into a spreadsheet for later processing.

The transmitter antenna for the Experimental Farm, Heron Bridge and Prince of Wales Drive measurements was mounted on the top of the Loeb building which is approximately 150 feet high. During the observations at the transit way of the Billings Bridge, Bronson Bridge, Campus Avenue, and University Drive the transmitter was mounted on the top of the Minto Case building which is approximately 40 feet high. The height of the receiving antenna from ground was 1.2m and had the provision of elevating it at different angles. The height of receiving antenna is measured from the ground during the measurements at the Experimental Farm, Prince of Wales Drive, Campus Avenue and University Drive. While the receiving antenna height is referenced from the Bridge during the measurements at Heron Bridge, Billings Bridge and Bronson Bridge.

As proposed cell size for initial LMCS systems are less than 2km, therefore the distances between transmitting antenna and receiving antenna during all measurements was kept between 200m to 1.7km.

The compass needle was used to know the direction of the transmitting antenna. The tuning and tracking of the right signal was done by using laptop through an automatic tuning program (written in LabView).

3.3.3 Observations

No fade and attenuation except free space loss was observed on a line of sight (LOS) link within 2km. However scenarios with trees and/or passing vehicles in between the transmitting and receiving antennas, resulted in the following qualitative observations.

3.3.3.1 Effects of foliage movements imparted from wind

- Heavy dense trees cause attenuation but do not produce much variation.
- Trees with green leaves (fresh alive) produce less variation as compared to trees with yellow and dehydrated leaves.
- Variation due to leaves is a continuous process. The signal continuously varies in a certain range.
- Coniferous (evergreen) trees when disturbed by wind produce slow fading, while deciduous trees produce faster fading.
- Fade depth is less than the variation due to passing vehicles. This is probably because of the attenuation of the foliage.
- 10% of the total acquired data showed no fading periods. These 10% of the data has been rejected and were not included for statistical analysis.

3.3.3.2 Effects of passing vehicles

- Fading is not a continuous process, and depends on traffic flow of the vehicles. On a busy street it might be continuous.

- Heavy vehicles such as buses and trailers cause comparatively deeper fades than small vehicles such as cars.
- Fade depth also depends on the distance between the receiving antenna and passing vehicles. When the distance between the receiver antenna and passing vehicles was one meter then the fade depth for heavy vehicles goes below the noise floor of the equipment (possibly because it blocks the receiving antenna completely). The depths were moderate when distance between passing vehicles and receiving antenna was 3 meter or more. Since most of the LMCS antennas are supposed to be well above the ground and far from the fast moving vehicle, the data analysed here for this scenario may show pessimistic results.
- Fade rate depends on the speed of the vehicle. Slow moving vehicles produce slow fading, while fast moving vehicles produce fast fading.
- Fade duration also depends on the distance between the receiving antenna and passing vehicles.
- Fading period were observed in 75% of the recorded data. The remaining 25% shows no variations, and has been exclude from statistical analysis.

The observations show that the performance of the link might degrade severely because of nearby passing vehicles, when one needs to provide LMCS services in down town area where the streets are very busy and buildings are close to the streets. Windy conditions can also cause some degradation in the performance of the LMCS systems.

3.4 DATA ANALYSIS

3.4.1 Procedure [16]

Data was recorded on each link for 10 minutes at the rate of 2k samples per second. This means that each link contains 1,200,000 samples. The processing of this many samples requires not only a lot of memory but is also very complex. In order to reduce the computational complexity, the acquired data is broken into 5 seconds subintervals (10000 samples). This makes the processing faster, easier and less complicated.

The acquired data is then calibrated into dBm units with the help of the calibration curve shown in figure 3.3. Linear interpolation has been used to calibrate the signal. Figure 3.3 shows that the useful dynamic range is from -52.90dBm to -108dBm.

Figure 3-3: Calibration Curve

In order to find the fluctuation range, maximum and minimum values of the signal strength were also calculated from the calibrated data. This curve is plotted for each of the six places in later section.

Since the event of fading is relatively rare, acquired data is decimated to avoid the biasing effect on fading statistics. For this purpose, the local mean of each 5-second subintervals was taken and then each half-second of the recorded data was scanned to find the total number of samples 3dB below or above the mean. If the number of samples in that half-second interval is greater than 15 then that interval was declared to be a fading interval and saved for later processing. Otherwise that half-second interval is removed from the 5 seconds subinterval.

The total amount of data we have exclude from the analysis is less than 10% for foliage and less 25% for passing vehicles. Therefore 90% of acquired were used to analyze the temporal variations because of foliage movement due to wind and 75% of the acquired were analyzed for the temporal variations caused by passing vehicles.

After extracting the fading intervals from each 5-second subinterval, signal analysis is done to find the following behavior of the signal;

1. Cumulative distribution function of the received signal strength
2. Time Autocorrelation function
3. Doppler spectrum
4. Cumulative Distribution Function of Fading Bandwidth

5. Level Crossing Rate
6. Fade Duration
7. Non-Fade Duration
8. Fall and Rise Time of the Fade

All these parameters were found separately for both foliage movement and passing vehicles scenarios. The procedures for finding these parameter are described below.

3.4.1.1 Cumulative distribution function of the received signal strength

In order to find the link cumulative distribution function of the received signal strength (the probability that the signal will drop below the threshold level), the probability density function of each 10 minute links has been computed from its histogram. The cumulative sum of these probabilities was taken to find the CDF of the received signal strength of the signal envelope.

3.4.1.2 AutoCorrelation

The samples in each subinterval (which contains only fading intervals after data reduction) are then converted into a linear amplitude scale using the following relationship.

$$R = \sqrt{10^{(RcvdSig_dBm \times 0.1)}} \text{ mVolts} \quad \text{Eq (3.15)}$$

The linear data is then normalized to its mean value.

$$R_n = \frac{\bar{R}}{R} \quad \text{Eq (3.16)}$$

Where $\bar{R}$ is the sample average of the observed data in linear scale. Time autocorrelation of the resulting normalized linear data is then calculated for each subinterval using the Matlab DSP toolbox with unbiased option for maximum lag of one second. Finally, the autocorrelation function of all subintervals for a given location is averaged to find the representative autocorrelation function of the given sites.

3.4.1.3 Doppler Power Spectrum (Power Spectral Density)

Power Spectral Density of the fading signal envelope is calculated by taking the Fourier transform of the time autocorrelation function of the subintervals. The resulting power spectrum of the fading signal envelope is then normalized to its maximum. The zeroth lag is then shifted to the center of the spectrum. The representative power spectrum of the fading signal envelope is found from the Fourier transform of the representative autocorrelation function.

3.4.1.4 CDF of Fading Bandwidth (Doppler Spread):

For each sub-interval, the bandwidth of the normalized received signal envelope for threshold levels of 3dB, 12dB, 21dB and 30dB below the peak is computed from the respective power spectral density. A histogram is then computed to find the cumulative sum of 3dB, 12dB, 21dB and 30dB fading bandwidth, from which the probability of fading bandwidth can be determined.

3.4.1.5 Level Crossing Rate

For computing the Level Crossing Rate (LCR), each fading subinterval was normalized and scanned to find samples below a threshold level ranging from -40 dB to +10dB. If a sample goes below this level a Flag is set which indicates that a level crossing occurred in the negative direction. When the level is exceeded, the same Flag is reset which indicates that a level crossing occurred in the positive direction. The LCR value is then normalized to the respective duration of the subinterval to find the number of crossings per seconds in both directions (positive and negative). The CDF of LCR for each subinterval is then computed whose 90th percentile, 99th percentile mean and median has been plotted against the threshold level relative to its mean.

3.4.1.6 Fade Duration

Fade duration for threshold ranging from -40 to +10dB has been found from the same procedure as used to find level crossing rate. Instead of counting number of crossings in both direction, number of samples between the negative and positive crossings were counted. To convert them into seconds the number of samples between negative and positive crossing has been divided by the sampling rate of the samples. The CDF of Fade duration is then computed for each threshold. The 90th percentile, 99th percentile, mean and median is then plotted against the threshold level relative to its mean.

3.4.1.7 Non-Fade Duration

Non-fade duration was calculated from the same subintervals which were used to find level crossing rate and fade duration. The procedure used for finding non-fade duration is similar to

the procedure for finding fade duration except that the samples were counted between the positive and negative crossings.

3.4.1.8 Fall and Rise Time of the Fade

Fall time of the fade is the time it takes to go to the minimum value after crossing the threshold level in downward direction. While rise time is the time it takes to cross the threshold in upward direction from the deepest level (figure 3-4 illustrate these times). In order to calculate the fall and rise times of the fade three markers are used: Fade Start, Fade Mid, and Fade End. Fade Start marker is set when the signal crosses the threshold in downward direction, while Fade Mid is set when the deepest value is obtained during the particular fade period and Fade End Marker is set when the signal level crosses the threshold in upward direction. Fall and Rise time is then calculate by counting the number of samples between these markers and normalizing them with the sampling rate. Since the sampling time of one sample is 0.5msec, fall or rise time of less than this could not be observed.

Figure 3-4: *Fall and Rise Time of the Fade Period*

3.4.2 Results

3.4.2.1 Effects of foliage movement because of wind

Field measurements were done for this scenario in the Experimental Farm, Heron Road and Carleton University near a railway crossing. The results are as follows.

3.4.2.1.1 Location-Power Profile

The location-power profile for each locations is shown in Figure 3-5. Figure 3-5(a) shows the power profile of the observations made on Rouelle Ashley in the Experimental Farm. This street is approximately at 1.7 km from the transmitter location. The minimum and maximum signal strength is 15dbm and 40dBm on this street. A variation range of the signal observed at the Morningside street in the Experimental Farm is shown in figure 3-5(b). This street is about 700m from the transmitter. Signal variation on this street was about 10-35dB. Figure 3-5(c) shows the fluctuation range of the observed signal at University Drive and Campus Avenue in the Carleton University. The transmitter and receiver for these locations were approximately 200-300m apart. The variation observed on these street was about 10-50dB. The power profile for the observations made at Heron bridge, which is around 700m far from the dormitory is shown in figure 3-5(d). The variation in the signal strength was about 5-30dB. In almost all observations the lowest value of the signal strength was approximately 102dB, which is near the noise floor of the equipment. However the maximum value of the signal strength at Heron bridge is comparatively 10dB less than the maximum value of signal strength at Carleton University and Experimental Farm. This is probably because of the heavy shadowing caused by the dense foliage in between transmitter and receiver at Heron bridge.

Figure 3.5 (a) : *Location-Power Profile (Ashley Street in Experimental Farm)*

Figure 3.5 (b) : *Location-Power Profile (MorningSide Street in Experimental Farm)*

Figure 3.5 (c) : *Location-Power Profile (University Drive and Campus Avenue in Carleton University)*

Figure 3.5 (d) : *Location-Power Profile (Heron Bridge)*

3.4.2.1.2 Typical Envelope Fading

Typical envelopes of fading for each locations are shown in Figure 3-6. Different behaviors were observed during the measurements at the Experimental Farm, Carleton University and Heron Bridge. The conditions under which the observation were made at these locations are as follows:

- As propagation measurements at the Experimental Farm were taken in late August and September, therefore two different conditions were observed. In August leaves were green during the data logging. While in September leaves were dehydrated and had started to fall off the trees.
- At Carleton University most of the trees were coniferous which have thick and heavy branches. The observations were recorded for these trees in both normal wind condition i.e wind speed of 10km/hr and extremely windy conditions i.e. wind speed of 20-50km/hr.
- At Heron measurements were taken in a dense forest of coniferous trees because of a nearby park.

As the observations for the effect of the foliage movement because of wind were made in different conditions, it is interesting to note that the envelope of the signal at the Experimental Farm shows comparatively faster variation. The envelope fading at Carleton university was very slow, while the envelope fading at Heron is a continuous process. Typical fading envelope for the Experimental Farm, Carleton University and Heron bridge are shown separately in figures 3-6(a),3-6(b) and 3-6(c) respectively.

Figure 3.6 (a) : *Envelope fading with time (Experimental Farm)*

Figure 3.6 (b) : *Envelope fading with time (Carleton University)*

Figure 3.6 (c) : *Envelope fading with time (Heron Bridge)*

3.4.2.1.3 Cumulative distribution function of the Received Signal Strength

Cumulative distribution functions of the received signal strength is shown figure 3.7(a)-(c). Each curve in figures 3.7(a)-(c) represents the CDF of a particular link established for 10 minutes duration at the Experimental Farm, Carleton University and Heron Bridge respectively. The average probability for the fade depth of 15dB below the local mean of each 10-minute link in the Experimental Farm is 0.1215, in Carleton University is 8.3×10^{-2} and on Heron Bridge is 6×10^{-3} . Whereas the average probabilities of fade depth of 30dB below the mean for the respective locations (Exp. Farms, Carleton University and Heron Bridge) are 2.7×10^{-3} , 8.2×10^{-3} and 2.0×10^{-3} . Since the probability of fade depth of 15dB is fairly high, link margin for the system design should be more than 15dB.

Figure 3.7 (a) : *CDF of Envelope Fading (Experimental Farm)*

Figure 3.7 (b) : *CDF of Envelope Fading (Carleton University)*

Figure 3.7 (c) : CDF of Envelope Fading (Heron Bridge)

3.4.2.1.4 Autocorrelation Function

Average time autocorrelation functions and the CDF of coherence time of the subintervals in each of the links observed in the Experimental Farm, Carleton University and Heron are shown in figure 3.8(a)-3.10(a) respectively. The average time autocorrelation function and the CDF of the aggregate coherence time at all locations are shown in figure 3.8(b)-3.10(b). The coherence time is defined either as the duration of time when the value of correlation coefficient is more than 0.1 or more than 0.05. The maximum magnitude of autocorrelation for most of the links at all locations is less than 0.2. The CDF of coherence time for foliage movement shows that the 90th percent of the time the signals at all locations are correlated for less than 0.2sec and 0.3sec with the correlation coefficients of more than 0.1 and 0.05 respectively. Though the time when the correlation drop to zero is 1sec, the correlation values after 0.1sec are insignificant at all locations.

Figure 3.8 (a) : Time Autocorrelation of Envelope Fading (Experimental Farm)

Figure 3.8 (b) : CDF of Coherence Time (Experimental Farm)

Figure 3.9 (a) : Time Autocorrelation of Envelope Fading (Carleton University)

Figure 3.9 (b) : CDF of Coherence Time (Carleton University)

Figure 3.10 (a) : Time Autocorrelation of Envelope Fading (Heron Bridge)

Figure 3.10 (b) : CDF of Coherence Time (Heron Bridge)

Figure 3.11 (a) : Time Autocorrelation of Envelope Fading for foliage movement

Figure 3.11 (b) : CDF of Coherence Time Envelope Fading for foliage movement

It can be concluded from this value that for a digital communication system in an environment where vegetation is expected, the channel will remain approximately time invariant or time flat for 0.01sec to 0.05sec. As the expected data rate for LMDS/LMCS is 20-40Mbps it is obvious that signal will undergo slow fading.

3.4.2.1.5 Power Spectral Density

Figure 3.12(a)-(c) shows the spectrum of the envelope power at the Experimental Farm, Carleton University and Heron Bridge. It is observed that the 40dB power spectrum bandwidth of the envelope signal is on the order of 400Hz to 800Hz for the observations made at the Experimental Farm, Carleton University and Heron Bridge. The average power spectrum of all three locations is shown in figure 3.12(d). It is found that on average 40dB fading bandwidth for the effect foliage movements is 500Hz approximately.

Figure 3.12 (a) : *Doppler Power Spectrum of Envelope Fading (Experimental Farm)*

Figure 3.12 (b) : *Doppler Power Spectrum of Envelope Fading (Carleton University)*

Figure 3.12 (c) : *Doppler Power Spectrum of Envelope Fading (Heron Bridge)*

Figure 3.12 (d) : *Doppler Power Spectrum of Envelope Fading for foliage movement*

3.4.2.1.6 Cumulative Distribution Function of Fading Bandwidth (Doppler Spread)

The CDFs of 3dB, 9dB and 15dB fading bandwidth for the Experimental Farm, Bronson bridge and Heron bridge are shown in figure 3.13(a)-(c). It is observed that the 99th percentile of 3dB and 9dB fading bandwidth for the observations at the Experimental Farm are less than 50Hz and 140Hz respectively. While the observation at the Carleton University shows that the fading bandwidths are less than 200Hz, 400Hz and 700Hz for the threshold levels of 3dB, 9dB, and 15dB respectively. The observation at the Heron bridge reveals that the fading bandwidths are less than 50Hz and 170Hz for the threshold levels of 3dB and 9dB respectively. The aggregate of 3dB, 9dB and 15dB fading bandwidth of the three location is shown in figure 3.13(d).

Figure 3.13 (a) : CDF of fading bandwidth of envelope fading (Experimental Farm)

Figure 3.13 (b) : CDF of fading bandwidth of envelope fading (Carleton University)

Figure 3.13 (c) : *CDF of fading bandwidth of envelope fading (Heron Bridge)*

Figure 3.13 (d) : *CDF of fading bandwidth of envelope fading for foliage movement*

3.4.2.1.7 Level Crossing Rate

The 99th percentile, 90th percentile, mean and median level crossing rates in both directions (below and above the threshold) at various threshold level of -40dB to +10dB are shown in figure 3.14(a)-3.14(c) for all locations. The level crossing rates at the Experimental Farm and Heron Bridge are approximately 600 crossings/sec at the mean. The rate of crossing the level for the observations at Carleton University is 250 crossings/sec at the mean. This difference is probably because of the deciduous trees between the transmitting and receiving antenna at the Experimental Farm and Heron Bridge and the coniferous trees at Carleton University. The aggregate level crossing rate (figure 3.14(d)) shows that on average at -10dB threshold the rate of crossing is 125 crossings/sec in both directions.

Figure 3.14 (a) : Level Crossing Rate (Experimental Farm)

Figure 3.14 (b) : Level Crossing Rate (Carleton University)

Figure 3.14 (c) : Level Crossing Rate (Heron Bridge)

Figure 3.14 (d) : Level Crossing Rate for foliage movement

3.4.2.1.8 Fade duration

Fade durations for different threshold levels with respect to the mean of each 5-sec subinterval are shown in figure 3.15(a)-(c) for the recorded data at the Experimental Farm, Carleton University, and Heron bridge. Figure 3.15(d) shows the aggregate fade duration of the three locations. The 99th percentile and mean fade duration for the threshold level at the mean of the subinterval for the three location are approximately; 2.1sec and 2.5msec, respectively at the Experimental Farm, 1.2sec and 5msec at Carleton university, 71msec and 0.5msec at Heron Bridge. The aggregate 99th percentile and mean fade duration of the three locations for threshold level of 0dB are 2.1 sec and 2.2msec respectively.

Figure 3.15 (a) : *Fade duration (Experimental Farm)*

Figure 3.15 (b) : *Fade duration (Carleton University)*

Figure 3.15 (c) : *Fade duration (Heron Bridge)* **Figure 3.15 (d) :** *Fade duration for foliage movement*

3.4.2.1.9 Fall and rise time of the fade

The fall and rise time statistics of the fading periods for the observation in the Experimental Farms, Carleton University and Heron Bridge are shown in figure 3.16(a)-3.16(d). It is observed that the 99th percent of the time fading periods in the Experimental Farms takes approximately 1.0 msec to reach the minimum level (depth) at the threshold level of -25 dB whereas the 99th percentile of the rise time of the fade at same threshold is 0.6 msec. The average values of fall and rise time of the fade periods in the Experimental farms is 2×10^{-2} sec at the mean. The observations at Carleton University show that the 99th percentile of both fall and rise time is 5 msec at -20 dB threshold level. The 99th percentile of both fall and rise time for the observation at Heron Bridge is 0.9 msec. While the average fall and rise time at the mean for Heron Bridge is 6 msec. On average the 99th percentile of fall and rise time for foliage movement is 2×10^{-2} sec and average fall and rise time is 2×10^{-2} sec at the mean.

Figure 3.16 (a) : Fall and Rise time (Experimental Farms)

Figure 3.16 (b) : *Fall and Rise time (Carleton University)*

Figure 3.16 (c) : *Fall and Rise time (Heron Bridge)*

Figure 3.16 (d) : *Fall and Rise time of the fade (foliage movement)*

3.4.2.1.10 Non-fade duration

Non-fade durations of the reduced data at the three locations are shown in figure 3.17 (a) -(c). The approximate value of the 99th percentile and the mean non-fade duration at the threshold level of 0dB (i.e. at the mean of the subinterval) for the respective locations are: as follows

- 0.7sec and 5.8msec at the Experimental Farm.
- 0.7sec and 9msec at the Carleton university.
- 0.25sec and 0.5msec at the Heron Bridge.

The aggregate 99th percentile and mean of the non-fade duration for the threshold level of 0dB are 2.2sec and 2.2msec respectively.

Figure 3.17 (a) : Non-fade duration during fading interval (Experimental Farm)

Figure 3.17 (b) : Non-fade duration during fading interval (Carleton University)

Figure 3.17 (c) : *Non-fade duration during fading interval (Heron Bridge)*

Figure 3.17 (d) : *Non-fade duration during fading interval for foliage movement*

3.4.2.2 Effects of passing vehicles

In order to find the effects of passing vehicles on the signal envelope, observations were made at Bronson Bridge, Prince of Wales Drive, and Heron bridge. The results obtained from the analysis of the data at these location are described below.

3.4.2.2.1 Location-Power Profile

The power profiles at the Bronson Bridge, Prince of Wales Drive and Heron Bridge are shown in figure 3.18(a)-3.18(d). The distance between transmitting and receiving antenna at the three locations was approximately 700 meters. The transmitting antenna was placed on Loeb building for the data recorded at Prince of Wales Drive and Heron bridge. While the transmitting antenna for the propagation measurements at the Bronson Bridge was placed on the top of the Minto-Case building. Since all the observed locations were at the same distance and the transmit and receive antennas had LOS, the maximum value of the signals on almost all links at the three location were same. The minimum value of the signal, however depends on the type of a passing vehicles. The fluctuation range of the signal is 3-40dB. Figure 3.18(a) shows the power profile of the signal observed at Bronson bridge. All variations at this location were the same except for the link number1. The probable reason is the alignments of the receiving antenna at the corner of the transmitting beam. Figure 3.18(b)-(c) show the power profile at Prince of Wales Drive. The signal fluctuations are in the range of 20-50dB, depending on the flow and the type of the passing vehicles. The power profile at Heron bridge shows that the fluctuation range of the signal strength is 25-45dB. It is interesting to note that the traffic signals at Heron and Bronson bridge are periodic, while the traffic signal at Prince of Wales Drive is automated (i.e., the light goes red only when a car or pedestrian is detected coming from the crossing road). This might be the reason of the varied power profile on each link at the Prince of Wales Drive and almost uniform signal strength at Bronson and Heron Bridge.

Figure 3.18 (a) : *Location-Power Profile (Bronson Bridge)*

Figure 3.18 (b) : *Location-Power Profile (Prince of Wales Drive 1)*

Figure 3.18 (c) : *Location-Power Profile (Prince of Wales Drive 2)*

Figure 3.18 (d) : *Location-Power Profile (Heron Bridge)*

3.4.2.2.2 Typical Envelope Fading

Typical envelope fading for 5sec intervals is shown in figure 3.19(a)-3.19(c) for Bronson bridge, Prince of Wales Drive and Heron bridge respectively. It can be observed from these figures that the event of fading in this case (effect of passing vehicles on signal strength) is not continuous process. At Bronson bridge data were recorded with no trees in between, which results in almost uniform signal strength when no vehicles passing the receiving antenna. Trees were avoided for the propagation measurements at Prince of Wales Drive and Heron Bridge. The small signal variation during no fading events at these locations is possibly because of scattering and multipath arrival of the signal due to the dense trees in the vicinity of these locations.

Figure 3.19 (a) : *Envelope fading with time (Bronson Bridge)*

Figure 3.19 (b) : *Envelope fading with time (Prince of Wales Drive)*

Figure 3.19 (c) : *Envelope fading with time (Heron Bridge)*

3.4.2.2.3 Cumulative distribution function of the Received Signal Strength

Cumulative distribution functions of the signal strength on each link of the three location are shown in figure 3.20(a)-3.20(c). It is observed that the average probability for received power 15dB below the mean of each link at Bronson bridge is 0.166, for Prince of Wales Drive is 0.22 and for Heron Bridge is 0.25. On average the probability that is the representative probability of fade depth of 15dB for vehicular traffic is 0.2 while the representative probability of same fade depth for foliage movement is 0.3. The average probabilities for the fade depth of 30dB below the mean of the respective location are 5.8×10^{-3} , 7.9×10^{-3} and 1.1×10^{-2} . the average probability of the 30dB fade depth is 8.2×10^{-3} while for foliage it was 4.3×10^{-3} .

Figure 3.20 (a) : CDF of envelope fading (Bronson Bridge)

Figure 3.20 (b) : *CDF of envelope fading (Prince Of Wales Drive)*

Figure 3.20 (c) : *CDF of envelope fading (Heron Bridge)*

3.4.2.2.4 Autocorrelation Function

Figures 3.21-3.23 show the average time autocorrelation functions and the CDF of coherence time for each of the links observed at three locations. The representative autocorrelation function and the CDF aggregate coherence time for the effect of passing vehicles are shown in figure 3.24. The coherence time is defined for the time during which the correlation are more that 0.1 and 0.05. It is interesting to note that the values of correlation for the effect of passing vehicles are approximately same as observed for the effect of foliage movement. The maximum value of the correlation of representative average autocorrelation function for the effect of passing vehicles is 0.12. The 90th percentile of the average coherence time for correlation of less 0.1 and 0.05 are 0.1sec and 0.22sec, respectively.

Figure 3.21 (a) : Time Autocorrelation of Envelope Fading (Bronson Bridge)

Figure 3.21 (b) : CDF of Coherence Time (Bronson Bridge)

Figure 3.22 (a) : Time Autocorrelation of Envelope Fading (Prince of Wales Drive)

Figure 3.22 (b) : CDF of Coherence Time (Prince of Wales Drive)

Figure 3.23 (a) : Time Autocorrelation of Envelope Fading (Heron Bridge)

Figure 3.23 (b) : CDF of Coherence Time (Heron Bridge)

Figure 3.24 (a) : Time Autocorrelation of Envelope Fading for passing vehicles

Figure 3.24 (b) : CDF of Coherence Time for passing vehicles

3.4.2.2.5 Power Spectral Density

The power spectral density for Bronson Bridge, Prince of Wales Drive and Heron Bridge is shown in figure 3.25 (a)-(b) and (c) respectively. The average power spectral density of the three locations is plotted in figure 3.25(d). It is observed that 40dB bandwidth of the power spectrum is 400Hz-800Hz for the observations at Bronson bridge except for one link which was aligned at corner of the transmitting beam. The 40dB power spectrum bandwidth is less than 400Hz for the data recorded at Prince of Wales Drive. The corresponding bandwidth is between 400Hz and 800Hz for the observation at Heron Bridge. The representative power spectrum shows that on average the bandwidth is 600Hz

Figure 3.25 (a) : *Doppler power spectrum of envelope fading (Bronson Bridge)*

Figure 3.25 (b) : *Doppler power spectrum of envelope fading (Prince of Wales Drive)*

Figure 3.25 (c) : *Doppler power spectrum of envelope fading (Heron Bridge)*

Figure 3.25 (d) : *Doppler power spectrum of envelope fading for passing vehicles*

3.4.2.2.6 Cumulative Distribution Function of Fading Bandwidth (Doppler Spread)

The CDFs of 3dB, 9dB and 15dB fading bandwidth for the three locations are shown in figure 3.26(a)-(c), respectively. It has been found that the 90th percentiles of 3dB and 9dB fading bandwidth at Bronson bridge are 25Hz and 55Hz respectively, and at Prince of Wales Drive were 13Hz and 23Hz respectively. At Heron bridge the 90th percentiles of 3dB, 9dB and 15dB fading bandwidth are 15Hz, 50Hz and 150Hz respectively. The aggregate CDF of 3dB, 9dB and 15dB fading bandwidth of the three locations is shown in figure 3.26(d). The respective 90th percentile of fading bandwidths are 15Hz, 40Hz and 100Hz.

Figure 3.26 (a) : CDF of fading bandwidth of envelope fading (Bronson Bridge)

Figure 3.26 (b) : CDF of fading bandwidth of envelope fading (Prince of Wales Drive)

Figure 3.26 (c) : CDF of fading bandwidth of envelope fading (Heron Bridge)

Figure 3.26 (d) : *CDF of fading bandwidth of envelope fading for passing vehicles*

3.4.2.2.7 Level Crossing Rate

The 99th, 90th percentiles, means and medians of level crossing rate in positive and negative directions at different threshold level relative to the mean of the subinterval for the three locations are shown in figure 3.27(a)-(c), respectively. The observation at the Bronson bridge shows that 99th, 90th percentile, mean and median of level crossing rate were 115, 60, 21 and 13 crossings/sec respectively at the threshold level of 0dB with respect to its mean. The respective level crossing rate for the observation at Prince of Wales Drive, at the same threshold level were 200, 100, 45 and 25 crossings/sec respectively. At the same threshold the respective level crossing rate for the observation at Heron Bridge were 325, 230, 90 and 30 crossings/sec. The aggregate of the respective level crossing rate (figure 3.27(d)) at the same threshold of 0dB for the three locations were 250, 83, 29 and 8.3 crossings/sec.

Figure 3.27 (a) : *Level Crossing Rate (Bronson Bridge)*

Figure 3.27 (b) : *Level Crossing Rate (Prince of Wales Drive)*

Figure 3.27 (c) : *Level Crossing Rate (Heron Bridge)*

Figure 3.27 (d) : *Level Crossing Rate for passing vehicles*

3.4.2.2.8 Fade duration

The 99th percentile and mean of the fade duration at various threshold level are shown in figure 3.28(a)-(c) for the three locations. The 99th and mean fade duration at the threshold level of 5dB below its mean for the three location are as follows:

- 1sec and 17.8msec for the observation at Bronson Bridge respectively
- 1.5sec and 8.5msec for the observation at Prince of Wales Drive respectively
- 2.5sec and 17.1msec for the observation at Heron Bridge respectively.

The aggregate 99th percentile, and mean values of fade duration for the three locations is shown in figure 3.28(d). The 99th percentile of fade duration was 2.5 sec, while the mean fade duration was 11.4msec.

Figure 3.28 (a) : Fade duration (Bronson Bridge)

Figure 3.28 (b) : Fade duration (Prince of Wales Drive)

Figure 3.28 (c) : Fade duration (Heron Bridge)

Figure 3.28 (d) : Fade duration for passing vehicles

3.4.2.2.9 Fall and rise time of the fade

The fall rise time statistics for the observation at Bronson Bridge, Prince of Wales drive and Heron bridge are shown in figure 3.29(a)-3.29(b). It has been found that the 99th percentile of fall and rise time of the fading periods at Bronson Bridge is 0.9msec at -25db threshold. The observations at Prince of Wales drive reveals that the 99th percentile of both fall and rise time 1.5msec. At the same threshold level of -25dB the 99th percentile of fall and rise time of the fading periods at Heron Bridge is 0.5msec. The 99th percentile of fall and rise time for passing vehicles (for all three locations) is 2×10^{-2} sec at threshold level of -25dB with respect to the mean, while the average value is 2×10^{-2} at the mean. It is interesting to note that almost all statistics of fall and rise are symmetric except for the observation at the Experimental Farms.

Figure 3.29 (a) : *Fall and Rise time (Bronson Bridge)*

Figure 3.29 (b) : *Fall and Rise time (Prince Of Wales Drive)*

Figure 3.29 (c) : *Fall and Rise time (Heron Bridge)*

Figure 3.29 (d) : *Fall and Rise time of the fade (Passing vehicles)*

3.4.2.2.10 Non-fade duration

Non-fade durations during the fading intervals at threshold level are shown in figure 3.30(a)-(c) for the three locations. The 99th percentile and mean non-fade duration at the threshold level of 5dB below with respect to the mean of the fading interval at the respective locations are: 2sec and 60msec respectively, for the observations at Bronson bridge, 3.6sec and 22msec respectively, at Prince of Wales Drive, and 1.3sec and 20msec for the observations at Heron Bridge

The aggregate of the respective non-fade durations of the three locations is shown in figure 3.30(d). The 99th percentile of the aggregate non-fade duration was 3.6sec, while the mean non-fade duration is 32msec.

Figure 3.30 (a) : Non-fade duration during fading interval (Bronson Bridge)

Figure 3.30 (b) : *Non-fade duration during fading interval (Prince of Wales Drive)*

Figure 3.30 (c) : *Non-fade duration during fading interval (Heron Bridge)*

Figure 3.30 (d) : *Non-fade duration during fading interval for passing vehicles*

3.4.3 Goodness of fit test for fading signal envelope

3.4.3.1 Procedure

The observed samples for fading signal envelope has been compared with following popular distribution functions for following wireless channel:

- Rayleigh
- Ricean
- Lognormal
- Nakagami

Closeness of the fit has been measured by performing the Kolmogorov-Smirnov[52] test for the significance level of 0.1. As the observed samples are in decibel units the comparison of the CDFs on a logarithmic scale is more accurate than the comparisons of CDFs on a linear scale[49]. The procedure for comparing theoretical empirical CDFs in logarithmic scale is as follows.

Let the observed samples in decibels be equal to Y i.e

$$Y = 20\log(R) \quad \text{Eq (3.17)}$$

$$Y = M\ln(R) \quad \text{Eq (3.18)}$$

where R = Received signal amplitude in volts and $M = \frac{20}{\ln 10}$.

The mentioned distribution functions on linear scale R are defined as follows [49][51].

Rayleigh Distribution Function

$$F_R(r) = 1 - \exp\left(-\frac{r^2}{2\sigma^2}\right) \quad \text{Eq (3.19)}$$

where R is the envelope of the received signal and σ^2 is the received signal power and can be evaluated from the mean square value of R .

$$E(R^2) = 2\sigma^2 \quad \text{Eq (3.20)}$$

Ricean Distribution Function

The distribution function of Ricean channel is given by:

$$F_R(r) = 1 - \exp\left(-\frac{s^2 + r^2}{2\sigma^2}\right) \sum_{m=0}^{\infty} \left(\frac{s}{r}\right)^m I_m\left(\frac{rs}{\sigma^2}\right) \quad \text{Eq (3.21)}$$

Where s and σ^2 are the parameters of Ricean distribution function and I_m is the modified Bessel function of the first kind and m^{th} order. If R is a Ricean random variable than R^2 is a non-central Chi-square random variable. Hence the parameters of a Ricean random variable can be evaluated from the moments of R^2

$$\mu = E(R^2) = 2\sigma^2 + s^2 \quad \text{Eq (3.22)}$$

$$v = E[(R^2 - \mu)^2] = 4\sigma^4 + 4\sigma^2 s^2 \quad \text{Eq (3.23)}$$

The parameters of Ricean are usually defined in terms of the K ratio, i.e.

$$K = \frac{s^2}{2\sigma^2} \quad \text{Eq (3.24)}$$

Log-Normal Distribution Function

$$F_R(r) = 1 - \frac{1}{2} \operatorname{erfc}\left(\frac{\ln r - \mu}{\sigma^2}\right) \quad \text{Eq (3.25)}$$

where μ and σ^2 are the mean and variance of the Log-Normally distributed random variable.

Nakagami m-Distribution Function

The distribution function of Nakagami random variable can not be expressed in closed form. However its distribution by definition is the integral of its density function

$$F_R(r) = \frac{2}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m \int_{-\infty}^x r^{2m-1} \exp\left(-\frac{mr^2}{\Omega}\right) dr \quad \text{Eq (3.26)}$$

where Ω is the mean square value of R

$$E(R^2) = \Omega \quad \text{Eq (3.27)}$$

and m is called the fading figure of Nakagami distribution function. It describes the amount of fading and is defined as the ration of the moments.

$$m = \frac{\Omega^2}{E[(R^2 - \Omega)^2]}, \quad m \geq \frac{1}{2} \quad \text{Eq (3.28)}$$

In order to find transformation of the mentioned distribution function in logarithmic scale we need to find the cumulative probability of the random variable Y in decibels i.e.

$$F_Y(y) = P(Y \leq y) \quad \text{Eq (3.29)}$$

Substituting the value of Y from eq. (3.18) we get,

$$F_Y(y) = P(M \ln R \leq y) \quad \text{Eq (3.30)}$$

$$F_Y(y) = P(R \leq \exp(y/M)) \quad \text{Eq (3.31)}$$

$$F_Y(y) = F_R(\exp(y/M)) \quad \text{Eq (3.32)}$$

Eq (3.31) shows that to transform the random variable R into Y , we need only to replace Y with $\exp(y/M)$ in the limits on the integral that defines the cumulative distribution function. The parameters of the distribution functions can also be derived in logarithmic scale, but this makes the transformation more complicated. Rayleigh and Log-normal distributions has been transformed with their parameters into Y . While the transformation for Nakagami is obtained from [49]. The Ricean distribution function is transformed for R only, i.e the parameters of the Log-Ricean distribution function are in linear scale.

The parameters of all random variables has been estimated from the observed samples i.e.

$$\hat{r} = E(r_{dB}) = \frac{1}{N_s} \sum_{i=1}^{N_s} r_{dB,i} \quad \text{Eq (3.33)}$$

$$v = \overline{(r_{dB} - \hat{r})^2} = \frac{1}{N_s} \sum_{i=1}^{N_s} (r_{dB,i} - \hat{r})^2 \quad \text{Eq (3.34)}$$

where N_s is the total number of samples in the observed fading interval.

The distribution function in Log-scale with the transformation of their linear parameters are given below.

Rayleigh Distribution on Log Scale

The probability density function of Raleigh random variable in logarithmic scale is derived as [49][51].

$$F_Y(y) = 1 - \exp \left[-\exp \left\{ \frac{2(y - \alpha)}{M} \right\} \right] \quad \text{Eq (3.35)}$$

where

$$\alpha = \hat{r} + 2.506 \quad \text{Eq (3.36)}$$

Log-Normal Distribution in Log Scale

$$F_Y(y) = 1 - \frac{1}{2} \operatorname{erfc} \left[\frac{y - \mu_{dB}}{2\sigma_{dB}} \right] \quad \text{Eq (3.37)}$$

where μ_{dB} and σ_{dB} are the mean and variance of random variable Y on logarithmic scale.

Nakagami m-distribution in Log Scale[49]

$$F_Y(y) = \frac{2m^m}{M\Gamma(m)} \int_{-\infty}^y \exp \left[m \left\{ \frac{2(u-\beta)}{M} - \exp \{ 2(u-\beta) \} \right\} \right] du \quad \text{Eq (3.38)}$$

where

$$\beta = \hat{r} - \frac{M}{2} \{ \psi(m) - \ln m \} \quad \text{Eq (3.39)}$$

$$\psi(x) = \text{digamma function} \quad \text{Eq (3.40)}$$

$$m = \frac{4.4}{\sqrt{\hat{v}}} + \frac{17.4}{\hat{v}^{1.29}} \quad \text{Eq (3.41)}$$

Beside testing the closeness of fit of each subintervals with the above mentioned distribution the parameters of each distribution for all subintervals are also determined.

For Rayleigh the parameters is given in Eq(3.36) and is determined as follows:

$$\alpha_{ray} = \text{mean}(\text{Normalised Received Signal strength in dB}) + 2.05 \quad \text{Eq (3.42)}$$

For Ricean the parameter is defined in Eq(3.24). Since the received signal strength R^2 is non-central chi-square-distributed[45], the parameters of Ricean random variable R can be calculated by using following equations[45]:

$$E(R^2) = n\sigma^2 + s^2 \quad \text{Eq (3.43)}$$

$$\text{Variance of } R^2 = V(R^2) = 2n\sigma^4 + 2\sigma^2s^2 \quad \text{Eq (3.44)}$$

s and σ are found by solving Eq(3.43) and Eq(3.44) simultaneously. The K ratio is then calculated by substituting the values of s and σ in Eq(3.24). The value of K ratio is then converted into log scale.

For Nakagami the parameter is defined in Eq(3.41):

$$m = \frac{4.4}{\sqrt{\text{Var}(\text{Received signal strength in dB})}} + \frac{17.4}{\text{Var}(\text{Received signal strength in dB})^{1.29}} \quad \text{Eq (3.45)}$$

3.4.3.2 Goodness of Fit test for the Effects of foliage Movement

Table 3.3 summarizes the results of goodness of fit test, using Kolmogorov-Smirnov method for the significance level of 0.1. The values of the parameters for each distributions are also computed.

It is observed that 21 subintervals in the Experimental farm passed Rayleigh, Ricean and Nakagami distributions (all three), with Rayleigh parameter of 1.9dB, Ricean parameter of 12.3dB and Nakagami parameter of 1.8. While in Carleton University 789 subintervals passed all three distributions (Rayleigh Nakagami, Ricean) with respective parameters of 2.09dB, 12.93dB, 2.09. In Heron, only 2 subintervals passed all three distributions with following respective parameters: 2.2dB, 14.6db, 3.03dB. However the percentage of passed subintervals for individual distributions are as follows: 97% links passed for Ricean distribution, while 79.6% of the links passed for Rayleigh distribution, 17% of the links fit Nakagami distribution and only 2% of the links passed KS test for Lognormal distribution in the Experimental Farm. The KS test for the observation in the Carleton University shows that 97% of the links passed for Ricean, 88% of the links passed for Rayleigh and approximately 2% of the links passed for Nakagami m-distribution. The 89% of the links at Heron bridge passed for Ricean, 46% for Rayleigh and around 3% for Nakagami. None of the link passed for Lognormal distribution for the observation at the Experimental Farm and Heron bridge.

Standard distributions which passed the KS test at the significance level of 0.1	Total number of subintervals passed KS test	Distribution Parameter
Experimental Farm, Total Number of Links = 56, Total Number of S-sec Subintervals= 5417		
Rayleigh	4131	1.4087dB
Nakagami	872	2.1091
Ricean	5079	11.7104
Log-Normal	94	-
Rayleigh+Ricean (overlapped)	554	$\alpha_{ray} = 1.667\text{dB}$, $K_{rce} = 11.01\text{dB}$
Rayleigh+Nakagami (overlapped)	21	$\alpha_{ray} = 1.013\text{dB}$, $m_{nak} = 1.07$
Ricean+Nakagami (overlapped)	21	$K_{rice} = 8.56\text{dB}$, $m_{nak} = 1.07$
Rayleigh+Ricean+Nakagami (overlapped)	21	$\alpha_{ray} = 1.9\text{dB}$, $K_{rce} = 12.3\text{dB}$, $m_{nak} = 1.8$
Carleton University, Total Number of Links = 47, Total Number of S-sec Subintervals= 4951		
Rayleigh	4385	1.5dB
Nakagami	802	1.63
Ricean	4778	10.4258
Log-Normal	0	-
Rayleigh+Ricean (overlapped)	4279	$\alpha_{ray} = 1.47\text{dB}$, $K_{rce} = 9.97\text{dB}$
Rayleigh+Nakagami (overlapped)	789	$\alpha_{ray} = 1.206\text{dB}$, $m_{nak} = 1.1125$
Ricean+Nakagami (overlapped)	793	$K_{rice} = 8.64\text{dB}$, $m_{nak} = 1.1125$
Rayleigh+Ricean+Nakagami (overlapped)	789	$\alpha_{ray} = 2.1\text{dB}$, $K_{rce} = 12.93\text{dB}$, $m_{nak} = 2.9$
Heron Bridge, Total Number of Links = 7, Total Number of S-sec Subintervals= 467		
Rayleigh	215	1.81dB
Nakagami	12	4.5
Ricean	416	13.4369dB
Log-Normal	0	-
Rayleigh+Ricean (overlapped)	210	$\alpha_{ray} = 1.85\text{dB}$, $K_{rce} = 11.8\text{dB}$
Rayleigh+Nakagami (overlapped)	2	$\alpha_{ray} = 0.8\text{dB}$, $m_{nak} = 0.94$
Ricean+Nakagami (overlapped)	7	$K_{rice} = 5\text{dB}$, $m_{nak} = 0.8$
Rayleigh+Ricean+Nakagami (overlapped)	2	$\alpha_{ray} = 2.2\text{dB}$, $K_{rce} = 14.6\text{dB}$, $m_{nak} = 3.03$

Table 3.3: Summary of Goodness of fit test for foliage movement

The overall result of Kolmogrov-Smirnov test for the significance level of 0.1, for foliage movement because of wind for all three locations is summarized as follows.

- Rayleigh distribution passed for 8731 out of 10835 subintervals (81%) with $\alpha_{ray} = 1.6\text{dB}$
- Ricean distribution passed for 10273 out of 10835 subintervals (95%) with K ratio of $K_{rce} = 12\text{dB}$ approx.
- Lognormal distribution passed for 94 out of 10835 subintervals (1%).
- Nakagami distribution passed for 1692 out of 10835 subintervals (16%) with $m_{nak} = 3$.

3.4.3.3 Goodness of Fit test for the Effects of the passing vehicles

The result of Kolmogrov Smirnov test is summarized in table 3-4 for the data recorded at Bronson bridge, Prince of Wales Drive and Heron Bridge respectively. It is observed that the number of subintervals in Bronson bridge passed all Rayleigh, Ricean and Nakagami distributions is 35, with Rayleigh parameter of 2.3dB Ricean parameter of 18.2dB and Nakagami parameter of 7.4. While 193 subintervals in Prince of Wales drive passed all three distribution (Rayleigh, Ricean, Nakagami) with respective parameters of 2.3dB, 22.7dB and 2.8. Only 16 subintervals from the observation at Heron bridge passed all three distributions with Rayleigh parameter of 1.9dB, Ricean parameter of 12.9dB, and Nakagami parameter of 2.8. The 19.2% of the links at Bronson bridge passed the KS test for Rayleigh distribution. While 16.5% of the links passed for Ricean distribution, 1.2% of the links passed for Nakagami distribution and

only one subinterval passed for Lognormal distribution. The KS test for the links at Prince of Wales Drive shows that 57% of the links passed Rayleigh distribution, 48.8% of the links passed Ricean distribution, 4% of the links passed the KS test for Nakagami distribution and only 0.2% of the links passed the KS test for Lognormal distribution. 36.3% of the links at Heron bridge passed KS test for Rayleigh distribution, 60% of the links fits Ricean distribution, 5% of the links passed KS test for Nakagami distribution and only 0.2% of the links fits the Lognormal distribution.

The overall results of the KS test for the significance level of 0.1, for passing vehicles for the three locations are as follows:

- Rayleigh distribution passed for 3897 out of 9218 subintervals (42.3%) with $\alpha_{ray} = 1\text{dB}$
- Ricean distribution passed for 3721 out of 9218 subintervals (40.3%) with $K_{rce} = 11\text{dB}$ (approx.).
- Lognormal distribution passed for 16 out of 9218 subintervals (0.1%).
- Nakagami distribution passed for 305 out of 9218 subintervals (3.3%) $m_{nak} = 1.5$.

Standard distributions which passed the KS test at the significance level of 0.1	Total number of subintervals passed KS test	Distribution Parameter
<i>Bronson Bridge, Total Number of Links = 27, Total Number of 5-sec Subintervals=2863</i>		
Rayleigh	551	1.4dB
Nakagami	36	1.3
Ricean	473	11.8dB
Log-Normal	1	-
Rayleigh+Ricean (overlapped)	400	$\alpha_{ray} = 1.254\text{dB}$, $K_{rce} = 9.762\text{dB}$
Rayleigh+Nakagami (overlapped)	35	$\alpha_{ray} = 1.58\text{dB}$, $m_{nak} = 1.40$
Ricean+Nakagami (overlapped)	36	$K_{rce} = 10.56, \text{dB}$, $m_{nak} = 1.40$
Rayleigh+Ricean+Nakagami (overlapped)	35	$\alpha_{ray} = 2.3\text{dB}$, $K_{rce} = 18.2\text{dB}$, $m_{nak} = 7.4$
<i>Prince of Wales Drive, Total Number of Links = 64 Total Number of 5-sec Subintervals= 4987</i>		
Rayleigh	2850	0.3139dB
Nakagami	203	1.6071
Ricean	2432	8.3125
Log-Normal	12	-
Rayleigh+Ricean (overlapped)	1989	$\alpha_{ray} = 0.936\text{dB}$, $K_{rce} = 8.925\text{dB}$
Rayleigh+Nakagami (overlapped)	193	$\alpha_{ray} = 1.448\text{dB}$, $m_{nak} = 1.2850$
Ricean+Nakagami (overlapped)	198	$K_{rce} = 10\text{dB}$, $m_{nak} = 1.29$
Rayleigh+Ricean+Nakagami (overlapped)	193	$\alpha_{ray} = 2.5\text{dB}$, $K_{rce} = 22.7\text{dB}$, $m_{nak} = 2.80$
<i>Heron Bridge, Total Number of Links = 18, Total Number of 5-sec Subintervals= 1368</i>		
Rayleigh	496	1.23dB
Nakagami	66	1.7349
Ricean	816	10.9851dB
Log-Normal	3	-
Rayleigh+Ricean (overlapped)	345	$\alpha_{ray} = 1.46\text{dB}$, $K_{rce} = 10.59\text{dB}$
Rayleigh+Nakagami (overlapped)	16	$\alpha_{ray} = 1.5\text{dB}$, $m_{nak} = 1.5$
Ricean+Nakagami (overlapped)	56	$K_{rce} = 9.7\text{dB}$, $m_{nak} = 1.76$
Rayleigh+Ricean+Nakagami (overlapped)	16	$\alpha_{ray} = 1.9\text{dB}$, $K_{rce} = 12.9\text{dB}$, $m_{nak} = 1.8$

Table 3.4: Summary of Goodness of fit test for passing vehicles

It should be noted that Ricean and Rayleigh are the special case of Nakagami distribution. So the subintervals which passed Rayleigh and Ricean distribution but fail to fit Nakagami distribution will likely had a non-optimum choice of parameters. The parameters for these test were chosen for the acquired data and no attempt was made to find the optimum choice of Nakagami parameters.

3.5 SUMMARY OF THE RESULTS

A brief summary of the measurement results are reported in this section. The effect of multipath is not very significant due to LOS directive antennas and antenna height (at least 30 feet). The fading statistics of time varying shadowing of broadband systems is expected to be similar or less than the narrowband systems. There may be two major causes of the time varying shadowing: foliage movement imparted from wind and vehicular traffic.

It was observed that the peak amplitude of the signal envelope is less for foliage movement than for vehicular traffic. This is possibly due to the shadowing of the foliage. The maximum fade depth for foliage movement is 40dB and for vehicular traffic is 50dB. The fade rate is higher for foliage movement than for vehicular traffic, because of the light structure of the foliage. The respective approximate average fade rate for foliage movement and passing vehicles at -30dB threshold is 0.065fades/sec and 0.13fades/sec. While the average fade duration due to foliage movement is 1msec and for vehicular traffic is 2.5msec.

The antenna height and their distance from the streets in the proposed LMCS architecture may render the effect of shadowing due to vehicular traffic insignificant. In case of densely populated and congested areas (for example down-town) it may not be possible to avoid such prob-

lems. Moreover, the wide-spread presence of trees and therefore the variations imparted by them in residential areas is difficult to avoid. For such cases, our study may help the system designers to incorporate the results in their system design. Despite these problems, the fading statistics show that with proper system design broadband service requirements can be achieved.

Kolmogrov-Smirnov tests were performed to find the closeness of fit of the CDF of the acquired data with the popular wireless channel distributions. It was observed that for foliage 81%, 95%, 1% and 16% CDF of the acquired data passed for Rayleigh, Ricean, Lognormal and Nakagami respectively. While for vehicular traffic 42%, 40%, 0.1% and 3.3% passed for Rayleigh, Ricean, Lognormal and Nakagami respectively.

Chapter 4

System Design Implications

In general, systems designed to accommodate the worst-case propagation conditions assume high error rates, which limit their capability to support high-speed data. The random nature of the wireless channel makes it difficult to guarantee quality and performance for demanding applications. However, a wireless system can be designed to adapt to the varying quality of the link, such that the system can support improved data rates and quality. Applications can also be designed to adapt to varying channel conditions to minimize the degradation seen by the user. The overall system can be optimized by making trade-offs among various performance measures such as BER, outage probability, and spectral and power efficiency. These trade-offs dictate the choice of modulation, signal processing, and antenna techniques used to mitigate channel impairments.

The radio frequency equipment for LMCS supports transmission of multiple carrier frequencies in the range of 28 GHz to 32GHz (in North America). The propagation measurements for temporal variations statistics of the signal discussed in the previous chapter were narrowband (CW) measurements at 29.5GHz. Thus we have not measured temporal variations over broad

bandwidths that would be used by LMCS systems. However, the variations that we observed were generally caused by moving foliage or vehicular traffic, which may be more in the nature of time-varying shadowing rather than time-varying multipath. Furthermore, LMCS systems will likely use highly directive antennas at least at subscribers' premises, further reducing the effects of multipath. For these reasons, we believe that the narrowband time variations that we measured are reasonably representative of what might be observed at broader bandwidth: e.g. several tens of MHz. We consider in this chapter the system design implications of the propagation characteristics reported in chapter 3. The chapter is organized as follows. In order to implicate the temporal variations statistics reported in the previous chapter, the fading statistics at various thresholds are given in section 4.1 In Section 4.2 some design parameters for power control algorithm, adaptive modulation, adaptive channel coding, interleaver and hybrid ARQ are suggested and performance of the suggested parameters is evaluated. Later the performance of the DAVIC 1.2 physical layer specification[57] is evaluated.

4.1 TEMPORAL VARIATION STATISTICS AT PARTICULAR THRESHOLD

Figures 3-7 and 3-20 show that the maximum fade depth below the mean is between 40dB to 30dB. Hence in order to design a digital communication system, we can have a link margin of 10dB to 40dB in the link budget of the system. In this section statistics of the time variation at these threshold are given, which will be used in later sections to design various system blocks. Table 4-1 summarizes the results presented earlier in chapter 3 (for example mean, median, 99th and 90th percentile of level crossing rate, fade duration, and non-fade duration) for various link margins.

Threshold level w.r.t mean (dB)	Average Probability (RRSL $\leq$ Threshold)	Fade Rate (fades/sec)	Fade duration (sec)	Non-fade duration (sec)
-5	0.42	105	2.29	3.3
-10	0.26	58	2.07	4.2
-15	0.16	31	1.66	4.42
-20	7.5×10^{-2}	35	0.625	4.5
-25	2.1×10^{-2}	12	0.193	3.9
-30	6.2×10^{-3}	7	0.055	4
-35	8.0×10^{-4}	0.27	0.0143	3.7
-40	4.0×10^{-4}	0.1 (approx.)	< 0.0005 (approx.)	<5(approx)

Table 4.1: 99th percentile of temporal variation statistics

The transceiver in a digital communication system is required to maintain a certain average power level to achieve a particular BER. Due to fading, interference and noise etc., the received signal level fluctuates around the average power. Therefore the transmitter power has to be such that the received average power is large enough to maintain the average BER throughout the service. This additional power of the mean above the performance is termed as Link Margin. This 'links margin' in most of the subsequent figures represents the ratio of the mean to the threshold in dB. For example table 4-1 shows the fading statistics at different threshold. In order to design the system for the fading statistics at -35dB threshold link margin of 35dB is required. In later sections the link margin indicates the additional amount of power required above the mean for particular performance metrics

4.2 LMCS SYSTEM - DESIGN AND PERFORMANCE EVALUATION

The performance measure of the link for a digital communication system with B-ISDN services are recommended in the G.826[34] standard. the subsequent section defines some of these parameters

4.2.1 Performance Parameters

The error performance parameters and events defined in G.826 recommendations are as follows [34]:

Bit Error Rate (BER): It is the ratio of number of bits in error to the total number of bits received.

Cell Loss Ratio (CLR): In ATM the frame structure is a cell. If 2 or more error corrupts the header of the cell, the whole payload is rejected. CLR is the ratio of number of cells lost because of corrupt headers to the total number of the cells received or transmitted.

Errored Block (EB): A block of data (frame, cell, packet) in which one or more bits are in error are termed as Errored Block

Error Second (ES): It is a one second duration with one or more error blocks.

Severe Error Seconds (SES): It is a one second period with 30% of Error Blocks or having at least one severely distributed period.

Severely distributed period (SDP): It is a one second period with 30% of Error Blocks or having at least one severely distributed period.

Background Block Error (BBE): An Error Block (EB) which does not occur during Severe Error Second (SES).

Error Second Ratio (ESR): It is the ratio of Error Seconds (ESs) to the total seconds in available time during a fixed measurements.

Severe Error Seconds Ratio (SESR): It is the ratio of Severe Error Seconds to total second in available time during a fixed measurement interval.

Background Block Error Ratio (BBER): It is the ratio of the Error Block (EBs) to total blocks during a fixed measurement interval, excluding all blocks during Severe Error Seconds and available time.

Appropriate interpretation of time varying statistics discussed in section 4.1 for certain digital communication blocks may help us to design the system to comply with the G.826 standard at low complexity. In the subsequent section we will discuss some power control algorithms, adaptive modulation schemes, choice of forward error correction methods, interleaver schemes and hybrid ARQ schemes.

4.2.2 Power control algorithm

Power Control aims to maintain the minimum signal level for transmission and reception with QoS guarantees. It also helps to improve the cochannel and adjacent channel interference and thus increase the system capacity. Once the power control mechanism detects a drop in the received power (a fade) it may take the following remedial actions:

- Command the transmitter to change the power level via a feedback channel.
- Command the transmitter to change the constellation size.
- Command the transmitter to change the code rate.
- Command the transmitter to change the interleaver depth.

One or a combination of two or more of the above techniques can be used to enhance the system performance and comply with the G.826 performance recommendations. Some simple power control algorithms has been suggested for the LMCS system in this section.

4.2.2.1 Assumptions

The following assumptions applying to all approaches discussed in subsequent sections. All schemes employ a closed loop centralized power or constellation size control of the modulation mechanism. That is, the transmitter changes the transmitted power based on the feedback messages from the receiving terminal. The following three approaches can be use for power control algorithm

4.2.2.2 Approach 1 (Periodic Scanning for Power Control)

The first approach for the power control algorithm is the periodic scanning or checking of the particular user. It works as follows:

Depending on the 90th or 99th percentile of fade rate at a certain threshold level (for example - 10 dB), the base-station would scan the channel at every t seconds i.e:

$$t = \frac{1}{n \times \text{fade rate}} \text{ seconds} \quad \text{Eq (4.1)}$$

(where n is a positive integer).

This scanning of the channel by the base-station should have a much higher rate than the fade rate (for example n should be at least 10). Scanning at a slower rate would result in missing few fade periods.

The spikes due to noise and interference can be mistaken as fade. This will lead to severe interference due to unnecessary increase in signal level. Such a problem can be avoided through the fall and rise time statistics of fading periods (as discussed in chapter 3). It is suggested that the base-station should observe the degradation in the signal level at least equal to the 90th percentile fall time of fade. The analysis of measurements shows that the 99th percentile of the fall time and rise time is 9msec. Hence the base-station should observe the fade for a minimum of 9msec before deciding the change in the power level of the user.

Power control messages requires bandwidth resources. Therefore it would be interesting to

investigate the amount of bandwidth consumed versus the benefits achieved. The bit rate required for upstream/downstream control messages is calculated as follows:

$$\text{Fade Rate} = \alpha \text{ fades/sec/user} \quad \text{Eq (4.2)}$$

$$\text{Scanning Rate} = n\alpha \text{ messages/sec/user} \quad \text{Eq (4.3)}$$

where n is a positive integer

$$\text{Scanning Rate} = n\alpha b \text{ bits/sec/user} \quad \text{Eq (4.4)}$$

where b is the control message length in bits.

For example, if $n = 10$, $\alpha = 2$, $b = 68 \times 8$ (length of time slot is 68 bytes in DAVIC).

$$\text{Scanning Rate} = 10 \times 2 \times 68 \times 8 = 10.88 \text{ kb/sec/user} \quad \text{Eq (4.5)}$$

The fade rates, α , for different threshold (link margin) values are given in table 4-1. Scanning overhead required at various link margins are calculated using Eq 4-3 for $n = 10$, 20 and $b = 68 \times 8$ bits (One RS coded ATM cell as per DAVIC recommendations). The calculated results for scanning overhead at various link margins are shown in figure 4-1.

Figure 4-1: *Scanning overhead of power control command at different link margin.*

Since a 1-2dB change in power results in the 10fold degradation of bit error rate of the modulation schemes, discrete level of power should be made for the change of 2dB or less. Also if we scan the channel at the fade rate then the power should have to drop back to its normal value after the 99th percentile of fade duration to avoid capture effect during non fade duration. For example, from chapter 3 the 99th percentile of the fade rate at -10dB threshold with respect to the mean is approximately 24 fades/sec. Therefore, the transmitter should issue the power control command to check the channel at least 24 times each second. In other words channel has to be scanned every 42msec to incorporate the variations in channel. This results in issuing the power control command in every 14th (for 3msec frame) or 7th (for 6msec frame) frames of DAVIC1.2 MAC recommendation[11] at 40Mbps to each individual user. It is important to note here that the number 42msecs is for the user operating at 29.5GHz frequency. If the scanning rate is 10 times the fade rate, the command would have to be issued at

about once per 3msec frame. It might be different for system operating at other frequencies in LMCS band.

This approach has following disadvantages:

- Because of delays in measuring received power and in feeding back the power command it is effective only for fairly slow fade rates (error corrections and interleaving are more effective for fast fade rates).
- It may skip fades of duration less than $t = \frac{1}{n \times f_{fade rate}}$ seconds. Where ($n \geq 10$).
- Frequent scanning of channel wastes spectrum, and consequently reduces utilization.
- Limited by possible saturation of power amplifiers.

4.2.2.3 Approach 2 (Power Control using Hybrid-ARQ)

Another approach is to use hybrid ARQ for controlling the power, rather than checking the channel periodically as in approach 1. When a user joins the network, its power is calibrated by the base-station. The user transmits at this power and no power control command is issued either to check the power or to change it. As soon as the transmitter or base station receives the retransmission request message or after response time out for a specific user, it will issue the power check and control command for that particular user. The user will calibrate (increase) its power accordingly and will continue to transmit at this power for a maximum fade duration at the defined threshold. For example, our analysis in previous chapter shows that the 99th per-

centile of the fade duration at -35dB below the mean is approximately 2msecs. Therefore that particular user will return to its normal calibrated power after 2msecs. This approach has the following advantages over the first approach:

- Less frequent power control message, consequently better link utilization
- Few re-transmissions are required than the first approach.
- Again, effective only for slow fade rates.

4.2.2.4 Approach 3 (BER based Power Control)

This is similar to the second approach. Instead of using the ARQ, the active users continuously check the channel BER. If the BER goes below the threshold (or standard recommended), the user will inform the base-station. The base-station will calibrate the new power level and will notify this value to the user. This approach appears more complicated than the second because the user is required to compute the BER of each received ATM cell and measuring BER takes considerable time.

4.2.3 Changing the power levels

Usually power control systems are provided with a N number of discrete levels of power at the receiver. Upon receiving the power control message the receiver switches to the level mentioned in the power control message. This scheme is more popular in practical communication system because of its simplicity and efficiency. Nevertheless, by increasing the power level, adjacent and cochannel interference increase. Also within the channel, it may cause some kind of capture effect over nearby users transmitting at low power, which has to be compensated.

4.2.4 Adaptive modulation scheme

Modulation is the process of encoding information into the amplitude, phase, and/or frequency of a transmitted signal. The choice of a modulation scheme for any system requires the consideration of spectral efficiency, error performance and system complexity. M-PSK and M-QAM are suitable candidates for LMCS because of their reasonable spectral efficiency, low complexity and hardware availability.

Instead of power level changes, adaptive constellation size i.e., M in M-PSK or M-QAM (also called adaptive modulation scheme) may be used to guarantee an acceptable BER. Compared to power control, these schemes are more complex. However adaptive modulation has the advantage that it does not affect interference to other signals. If the system is operating at maximum power level and required BER is not achieved then a hybrid of adaptive modulation and power control scheme could be used.

In order to evaluate the performance of the adaptive modulation scheme, we need to define the average BER required to satisfy the QoS guarantees. CCITT recommendations define the reference performance measures which can be used to judge the practical gains using the adaptive modulation. However, for a general discussion we assume that a BER of 10^{-6} is required.

Example 4-2: Phase Shift Keying

For M-PSK modulation, with the constellation size of $M = 128$ the required average signal to

noise ratio $\frac{E_b}{N_o} \Big|_{avgreq}$ can be computed as:

$$\left. \frac{E_b}{N_o} \right|_{avgreq} = \left(\frac{1}{2k} \right) \left(\frac{Q^{-1}\left(\frac{kP_b}{2}\right)}{\sin\left(\frac{\pi}{M}\right)} \right)^2 \quad \text{Eq (4.6)}$$

where $k = \log_2 M$,

P_b = required bit error probability

Hence for $P_b = 10^{-6}$ and $M = 128$:

$$\left. \frac{E_b}{N_o} \right|_{avgreq} = 33.79 \text{ dB} \quad \text{Eq (4.7)}$$

Now we can find the average required signal to noise ratio $\left. \frac{S}{N} \right|_{avgreq}$ for BER of 10^{-6} as:

$$\left. \frac{S}{N} \right|_{avgreq} = k \left(\frac{E_b}{N_o} \right) \quad \text{Eq (4.8)}$$

where k = number of bits in the constellaion

For $k = 7$

$$\left. \frac{S}{N} \right|_{avgreq} = 42.24 \text{ dB} \quad \text{Eq (4.9)}$$

If the bandwidth of the receiver is assumed to be $B = 40\text{MHz}$, and the noise figure $Nf = 1.5 = 2\text{dB}$, then at 300°K the noise power of the receiver can be calculated as:

$$N = KTB Nf \quad \text{Eq (4.10)}$$

where K = Boltzman constant

$$N = 2.5 \times 10^{-13} = -126\text{dBW} \quad \text{Eq (4.11)}$$

As the signal to noise ratio is defined as:

$$\left. \frac{S}{N} \right|_{\text{avgreq}} = RSL - N \quad \text{Eq (4.12)}$$

where RSL = Received Signal Level (dBW).

This means that the average required signal level for the BER of 10^{-6} is:

$$RSL = \left. \frac{S}{N} \right|_{\text{avgreq}} + N \quad \text{Eq (4.13)}$$

From equation(4.4) and (4.6)

$$RSL_{avgreq} = -83.756dBW \quad \text{Eq (4.14)}$$

Similarly we can calculate the minimum acceptable received signal level by defining a high acceptable bit error rate 10^{-3} for constellation size of $M = 8$:

$$RSL_{min} = -118.66dBW \quad \text{Eq (4.15)}$$

Normalizing the minimum required RSL_{min} with the average required RSL_{avgreq} we get the threshold w.r.t. average received signal strength.

$$L_{thr} = RSL_{min} - RSL_{avgreq}$$

$$L_{thr} = -34.91dB \quad \text{Eq (4.16)}$$

The performance for different constellation sizes of PSK modulation scheme is shown in figure 4-2. The gain in (E_b/N_o) between two consecutive constellation for same BER is about 5 dB. Therefore for a threshold level of $27dB$ below the mean, 7 intermediate levels of threshold can be defined for different constellation of PSK signals. This means that at or above threshold level 1 signal constellation could be $M = 128$, between threshold level 1 and 2 signal constellation could $M = 64$ and so on (figure 4-3).

Figure 4-2: Probability of bit error for PSK signals

Figure 4-3: Adaptive modulation of PSK scheme

The algorithm works as follows: If the received signal strength w.r.t to the mean (which is the feedback of power control messages) or operating threshold is less than or equal to 5 dB the modulator will reduce its constellation size by one bit. However, if its strength is 10 dB less or equal to the operating threshold, then the modulator will reduce the constellation size by 2 bits and so on. The error performance of such system can be evaluated from the probability of crossing the threshold. That is, we know from chapter 3 that the average probabilities for both scenario (i.e passing vehicles and moving foliage) that the received signal strength w.r.t the mean $RRSL$:

$$\begin{aligned}
 p_1 &= P(RRSL \geq 0) = 0.2841 \\
 p_2 &= P(-5 < RRSL < 0) = 0.2651 \\
 p_3 &= P(-10 < RRSL < -5) = 0.1588 \\
 p_4 &= P(-15 < RRSL < -10) = 0.1165 \\
 p_5 &= P(-20 < RRSL < -15) = 0.0956 \\
 p_6 &= P(-25 < RRSL < -20) = 0.0588 \\
 p_7 &= P(RRSL < -25) = 0.0218
 \end{aligned}
 \tag{4.17}$$

Hence the BER for average $\frac{S}{N} = 42.24dB$ at all these threshold level with different constellation size is computed as:

At level 1 ($M = 128$) (for threshold level dB above the mean) $Pb_1 \geq 1.00 \times 10^{-6}$

At level 2 ($M = 64$) (signal level 5dB below the mean) $Pb_2 = 4.8 \times 10^{-7}$

At level 3 ($M = 32$) (signal level 10dB below the mean) $Pb_3 = 3.2 \times 10^{-7}$

At level 4 ($M = 16$) (signal level 15dB below the mean) $Pb_4 = 3.9 \times 10^{-7}$

At level 5 ($M = 8$) (signal level 20dB below the mean) $Pb_5 = 1.5 \times 10^{-6}$

At level 6 ($M = 4$) (signal level 25dB below the mean) $Pb_6 = 4.9 \times 10^{-5}$

At level 7 ($M = 2$) (signal level below 25dBw.r.t the mean) $Pb_7 = 0.0286$

Hence the average BER is:

$$\begin{aligned} \hat{BER} &= \sum_{i=1}^7 (pb_i \times p_i) \\ \hat{BER} &= 6.2769 \times 10^{-4} \end{aligned} \quad \text{Eq (4.18)}$$

And, the average number of bits per symbol can be found as:

$$\begin{aligned} \hat{k} &= (7 \times p_1) + (6 \times p_2) + (5 \times p_3) + (4 \times p_4) + (3 \times p_5) + (2 \times p_6) + (1 \times p_7) \\ \hat{k} &= 5.265 \text{ bits/symbol} \end{aligned} \quad \text{Eq (4.19)}$$

The performance of the system can be compared with QPSK modulation at all levels. The average BER for QPSK modulation only is found to be 1.08×10^{-6} (using the same procedure as for Eq(4-13) Hence:

$$\frac{BER_{adp}}{BER_{QPSK}} = \frac{6.3 \times 10^{-4}}{1.08 \times 10^{-6}} \approx 583 \quad \text{Eq (4.20)}$$

$$\frac{k_{adp}}{k_{QPSK}} = \frac{5.26}{2} \approx 2.63 \quad \text{Eq (4.21)}$$

The calculations show that the BER performance of adaptive modulation scheme is slightly worse than QPSK modulation. While spectral efficiency is 2.6-fold better. The spectral efficiency might be less than the values shown here, because for adaptive modulation the modulation control command will consume some bandwidth (which ordinary QPSK scheme does not need). The adaptive scheme is more complex to implement than the QPSK modulation because of the multiple constellation level and issuance of modulation control command.

The above system for adaptive modulation is designed for average power level without considering any additional power provided to the system as link margin to combat fading, shadowing etc. If the system is provided with an additional power x dB then following three alteration to the configuration of the above mentioned system (figure 4-3) are possible:

- Case 1:** Maximum constellation size increases with an increase of 5dB power (link margin) to the above mentioned system (4-3) average power.
- Case 2:** Maximum constellation size decreases with an increase of 5dB power (link margin) to the average power of the above mentioned system (figure 4-3)
- Case 3:** Maximum constellation size remain constant with an increase of 5dB power (link margin) to the average power of the above mentioned system (figure 4-3)

Case 1: Increase maximum constellation size

The changes in the basic configuration of the system in figure 4-3 is shown in figure 4-4. In this case as the link margin increase to 5dB, the maximum constellation size of the modulation scheme also increases by one bit, i.e., from $M = 128$ to $M = 256$. The probability that the relative received signal strength is in the discrete level L is the same as in figure 4-3.

Figure 4-4: Case -1: Adaptive modulation of PSK scheme for increase in maximum constellation size with increase in link margin

The probability of bit error for the given constellation at each level L is then calculated using following expression[45]:

$$Pb(i) = 2Q\left(\sqrt{2 \log_2(M(i)) \left(\frac{E_b}{N_o}\right)} \sin\left(\frac{\pi}{M(i)}\right)\right) \quad \text{Eq (4.22)}$$

where i is the different levels from 1 to 7. The average BER and average spectral efficiency are then computed using Eq(4.18) and Eq(4.19) respectively. Figure 4-5 shows the calculated average BER and average number of bits per hertz. It can be observed that in this case the average BER ranges between 10^{-3} and 10^{-6} . For the link margin 5dB it improves then degrades at all other link margin. This is possibly because the BER degrade rapidly for higher constellation. (That is at higher constellations the gain between two consecutive constellation is less than 5dB).

Figure 4-5: (a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of M-PSK at different link margin (case 1)

Case 2: Decrease maximum constellation size

In this case the constellation size is decreased by one bit with an increase in link margin of 5dB. That is, if link margin is increase to 5dB, then constellation size will decrease from $M = 128$ to $M = 64$. The configuration of the constellation size with increased link margin is shown in figure 4-6. It should be noted that in this case the number discrete levels also decrease each time when link margin is increased to 5dB. The configuration in figure 4-3, has 7 discrete levels of constellation size ($M = 128$ to $M = 2$), while the configuration in figure 4-6 has 6 discrete level of constellation size $M = 64$ to $M = 2$ at 5db link margin, and has 5 discrete level at 10dB link margin and so. For link margin of 30db the system is operation for $M = 2$ only.

Figure 4-6: Case -2: Adaptive modulation of PSK scheme for decrease in maximum constellation size with increase in link margin

Similar approach as described above in case 1 is used to find the average BER and spectral efficiency of this system. The results for average BER and average number of bits transmitted per Hertz are shown in figure 4-7.

The performance curves in figure 4-7 show that the average BER improves sharply with increase link margin, however the spectral efficiency degrades almost linearly. This type of configuration may be use for the applications, which require high reliability and reasonable spectral efficiency.

Figure 4-7: (a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of M-PSK at different link margin (case 2)

Case 3: Constant maximum constellation size

In this case, with each 5dB increase in link margin, the maximum constellation size is used in again in the subsequent discrete level, and discard the lowest constellation size of $M = 2$. For example if link margin is 5dB, then $M = 128$ will be used in discrete level $L = 1$ and $L = 2$, while the constellation size at discrete level $L = 7$ is $M = 4$, similarly if link margin is 10dB then $M = 128$ will be used in discrete levels $L = 1, 2, 3$ and the at $L = 7$ the constellation size will be $M = 8$, and so on. At the link margin of 30dB the system will operate on the same constellation size of $M = 128$. The configuration of this case is shown in figure 4-8.

Figure 4-8: Case -3: Adaptive modulation of PSK scheme for same maximum constellation size with increase in link margin

The performance of this system is calculated using the same approach as in case 1. The average BER and spectral efficiency at different margin is shown in figure 4-9. The performance curves shows that after link margin of 10dB the average BER drops slowly, while the spectral efficiency improves from 5bits/Hz to 7bits/Hz. It should be noted that in case 1, spectral efficiency is high but at the cost of poor BER, in case 2 the average BER rate is fairly high but shows very poor spectral efficiency, while case 3 shows good spectral efficiency and improved BER. For example at 10dB link margin, $BER = 10^{-12}$ for case 1, $BER = 10^{-6}$ for case 2 and $BER = 10^{-7}$, while the spectral efficiency at the same link margin of 10dB, $k = 7.3$ for case 1, $k = 3.4$ for case 2, and $k = 6.4$ for case 3.

Example2: Quadrature Amplitude Modulation

A similar approach can be used for an adaptive constellation size of rectangular QAM. For

$M = 4096$, the required value of $\left. \frac{E_b}{N_o} \right|_{avgreq}$ can be calculated by using the following expression[45]:

$$\left. \frac{E_b}{N_o} \right|_{avgreq} = \left(\frac{M-1}{3K} \right) \left(Q^{-1} \left(\frac{P_b \sqrt{M}}{2(\sqrt{M}-1)} \right) \right)^2 \quad \text{Eq (4.23)}$$

where, $K = \log_2 M$ for $M = L^2$

P_b = required bit error probability .

For $P_b = 10^{-6}$ and $M = 4096$:

$$\left. \frac{E_b}{N_o} \right|_{avgreq} = 2.7184 \times 10^3, \text{ or } 34.3431 \text{ dB} \quad \text{Eq (4.24)}$$

The average required signal to noise ratio $\left. \frac{S}{N} \right|_{avgreq}$ is:

$$\left. \frac{S}{N} \right|_{avgreq} = 3.2621 \times 10^4 = 45.1349 \text{ dB} \quad \text{Eq (4.25)}$$

The average required signal level for the BER of 10^{-6} is:

$$RSL = 45.134 - 126 = -80.861 \text{ dBW} \quad \text{Eq (4.26)}$$

Similarly for a high bit error rate of 10^{-3} , the minimum acceptable received signal level for constellation size of $M = 4$ ($k = 2$):

$$RSL_{min} = -108.88 \text{ dBW} \quad \text{Eq (4.27)}$$

Normalizing the minimum required RSL_{min} with the average required RSL_{avgreq} we get the

threshold w.r.t. average received signal strength.

$$L_{thr} = -28.091dB \quad \text{Eq (4.28)}$$

The performance for different constellation size of rectangular (even number of bits) QAM modulation scheme is shown in figure 4-9. The gain in S/N between two consecutive constellations for the same BER is 6-7dB. We may have 5 or 6 levels of threshold. If the signal level goes 6dB below the mean then constellation size is reduced by 2 bits. The constellation level is shown in figure 4-10

Figure 4-9: Probability of bit error for QAM signals

Figure 4-10: Adaptive modulation of QAM scheme

Applying the same techniques used for PSK, the average BER can be calculated for QAM. The probabilities of crossing the levels are, from chapter 3,

$$\begin{aligned}
 p_1 &= P(RRSL \geq 0) = 0.2841 \\
 p_2 &= P(-7 < RRSL < 0) = 0.3372 \\
 p_3 &= P(-14 < RRSL < -7) = 0.1811 \\
 p_4 &= P(-21 < RRSL < -14) = 0.1328 \\
 p_5 &= P(-28 < RRSL < -21) = 0.0545 \\
 p_6 &= P(-35 < RRSL < -28) = 0.0083 \\
 p_7 &= P(RRSL < -35) = 0.0018
 \end{aligned}
 \tag{4.29}$$

Hence the BER at all these thresholds level with different constellation sizes is computed as:

At level 1 ($M = 4096$) (for threshold level above the mean) $Pb_1 \geq 8.33 \times 10^{-8}$

At level 2 ($M = 1024$) (signal level 7dB below the mean) $Pb_2 = 6.5 \times 10^{-6}$

At level 3 ($M = 256$) (signal level 14dB below the mean) $Pb_3 = 1.66 \times 10^{-4}$

At level 4 ($M = 64$) (signal level 21dB below the mean) $Pb_4 = 1.9 \times 10^{-3}$

At level 5 ($M = 16$) (signal level 28dB below the mean) $Pb_5 = 0.0119$

At level 6 ($M = 4$) (signal level 35dB below the mean) $Pb_6 = 0.0474$

At level 7 ($M = 4$) (signal level below 35dBw.r.t the mean) $Pb_7 = 0.1395$

Hence average BER is:

$$\hat{BER} = \sum_{i=1}^7 (pb_i \times p_i) \quad \text{Eq (4.30)}$$

$$\hat{BER} = 9.2 \times 10^{-5} \quad \text{Eq (4.31)}$$

And, the average number of bits per symbol can be found as:

$$\hat{k} = (12 \times p_1) + (10 \times p_2) + (8 \times p_3) + (8 \times p_4) + (4 \times p_5) + (2 \times p_6) + (2 \times p_7) \quad \text{Eq (4.32)}$$

$$\hat{k} = 10.61 \text{ bits/symbol} \quad \text{Eq (4.33)}$$

The performance of the system can be compared with QPSK/4-QAM modulation at all levels.

The average BER for QPSK modulation only is found to be 1.08×10^{-6} . Hence:

$$\frac{BER_{adp}}{BER_{QPSK}} = \frac{1.66 \times 10^{-3}}{1.08 \times 10^{-6}} = 1537 \quad \text{Eq (4.34)}$$

$$\frac{k_{adp}}{k_{QPSK}} = \frac{10.61}{2} = 5.30 \quad \text{Eq (4.35)}$$

The results for QAM shows that the BER is 1537 times worse than the ordinary QPSK modulation. While its spectral efficiency 5.3 times better than spectral efficiency of QPSK. Even with the waste of some spectrum on power control commands the spectral efficiency gained are significant.

Similar approach and cases are used to evaluate the performance of QAM with increase link margin. The only difference is that the link margin is in step 7dB instead of 5dB. The performance for each cases (for details on for each case please refer example1 of this section) are shown in figure 4-11 to 4-13.

It can be observed that for case 1 (which is increase in constellation size with increase in link margin) the BER performance for M-QAM is in order of 10^{-3} , while for case 2 (which is decreases in constellation size with increase in link margin), BER performance improves sharply, and for case 3 (which constant maximum constellation size with increase in link margin) BER performance improves gradually. All three case for M-QAM shows worse BER performance than for all three cases for M-PSK, while the spectral efficiency is twice better for M-QAM case than M-PSK cases.

Figure 4-11: (a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of rectangular M-QAM at different link margin (Case 1)

(a)

(b)

Figure 4-12: (a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of rectangular M-QAM at different link margin (Case 2)

(a)

(b)

Figure 4-13: (a) Probability of bit error and (b) spectral efficiency for adaptive constellation size of rectangular M-QAM at different link margin (Case 3)

Conclusions (adaptive modulation)

Though the adaptation of constellation size with the variation in the channels seems promising in maintaining the BER, it has the following shortcomings:

- This scheme can only operate in discrete level (i.e 5dB for M-PSK and 6dB for M-QAM).
- The range of constellation sizes considered here is large (4 to 128 to 4 to 4096). A small range is likely more practical (e.g. 4 to 64), supplemented by additive error correcting code rate.

4.2.5 Forward Error Correction

Low BER is difficult to achieve only through the use of modulation schemes alone. This leads to the use of forward error correction schemes, which helps to achieve the desired performance for different broadband applications. Channel coding improves performance by adding redundant bits in the transmitted bit stream that are used by the receiver to correct errors introduced by the channel, thus reducing the average BER. This approach enables a reduction in the transmit power required to achieve a target BER.

Though the spectral efficiency will be slightly affected because of the redundant bits to correct errors, the coding gain can significantly high. The choice of proper error control codes requires the characterization of the channel. That is we need to know the expected types of errors, for example random error, burst error etc. Pure burst correction codes are sensitive to the presence of random errors. However, in this section we will suggest some coding parameters based on

the results obtained in chapter 3 for popular coding schemes. The following assumptions were made to design the code.

Assumptions

Cell Loss ratios required by most of the B-ISDN services[4]:

$$\begin{aligned} CLR_{min} &= 10^{-9} \\ CLR_{max} &= 10^{-3} \end{aligned} \quad \text{Eq (4.36)}$$

Since all patterns of one erroneous bit can be corrected in an ATM cell header because of its (40,32) CRC, probability of error in the cell header can be calculated from the following expression, assuming the errors are random:

$$P_{cls} = \sum_{i=t+1}^n \binom{n}{i} P_b^i (1 - P_b)^{n-i} \quad \text{Eq (4.37)}$$

Where: n = Length of the Header = 40 bits

t = Error correction capability of CRC = 1

$$P_{cls} = 10^{-9}$$

P_b = Bit error probability

Substitution the values in Eq (4.37) we get:

$$10^{-9} = \sum_{i=2}^{40} \binom{40}{i} P_b^i (1 - P_b)^{40-i} \quad \text{Eq (4.38)}$$

Since Eq (4.37) is dominated by the first term of the summation and for small values of P_b the term $(1 - P_b) \sim 1$, we can approximate it as:

$$10^{-9} > \binom{40}{2} P_b^2 \quad \text{Eq (4.39)}$$

So P_b should be less than

$$P_b < \sqrt{\frac{10^{-9}}{780}} = 1.1323 \times 10^{-6} \quad \text{Eq (4.40)}$$

This means that the probability of bit error seen by the decoder should be less than 10^{-6} in order to maintain the CLR requirement of the B-ISDN services. The desired BER of less than 10^{-6} can be achieved through the use of forward error correction.

4.2.5.1 Reed Solomon Codes

Reed Solomon codes are extremely powerful q^m (non binary) BCH codes of length $q^m - 1$. These codes work over Galois field $GF(q^m)$. The value of $m = 8$ and $q = 2$ is an industry standard, as it corresponds to one byte with binary computation. These codes works in symbol so they correct bursts of bit errors affect certain symbols over certain symbols length or random error in each symbols. Also these codes are maximal distance codes and any modification to extend, shorten, puncture or augment the code does not effect its minimum distance. Because of its capability of correcting burst as well as random error these codes are very popular in industry especially in wireless communications.

Parameters

The parameters of a Reed-Solomon code are:

$$\text{Length of Code word} = n = 2^m - 1 \text{ symbols}$$

$$\text{Packet length} = k \text{ symbols}$$

$$d_{min} = n - k - 1 \text{ symbols}$$

$$\text{Code Rate} = R_c = \frac{k}{n}$$

Eq (4.41)

These codes can correct up to

$$\text{Error Correction} = t = \left\lfloor \frac{1}{2}(d_{min} - 1) \right\rfloor = \left\lfloor \frac{1}{2}(n - k) \right\rfloor \text{ symbols,}$$

Eq (4.42)

where $\lfloor x \rfloor$ mean the largest integer less than or equal to x

Code Performance

The performance of the RS code depends upon the value t and channel error probability. The expressions for symbol and bit error probability of RS code are:

$$P_s = \frac{1}{n} \sum_{i=t+1}^n i \binom{n}{i} (P_{chs})^i (1 - P_{chs})^{n-i}$$

$$P_b = \frac{2^{m-1}}{2^m - 1} P_s \quad \text{Eq (4.43)}$$

The length of code word is bounded by the following equation:

$$1 + 2t \leq n \leq 255 \quad \text{Eq (4.44)}$$

Depending on the value of t , n can be chosen between 3 to 255. However, because of the hardware complexity of the decoder the maximum value of t in the industry is 10. For example AHA provides single chip solution of RS code in which the number of correctable symbol errors (t), and block length (n) is set by the user within the mentioned range. The performance of the code for different error correction capability is shown in figure 4-14 for various channel error probability.

Figure 4-14: Performance of the RS Code for different Error Correcting Capabilities

RS code for LMCS

The 90th percentile of fade durations in bytes at different threshold for various data rate 10 to 40 Mbps are shown in table 4.2.

Threshold level w.r.t mean (dB)	Fade duration (sec)	Fade duration (bytes) at following data rate			
		10Mbps	20Mbps	30Mbps	40Mbps
-5	2.29	2.8M	5.6M	8.4M	11.2M
-10	2.07	2.6M	5.2M	7.8M	10.4
-15	1.66	2M	4M	6M	8M
-20	0.625	780K	1.5M	2.3M	3.1M
-25	0.193	240K	480K	720K	960K

Table 4.2: Fade duration in bytes at different data rates

The point should be remembered that our measurements were narrowband which could be an upper bound on fade duration. However these long fade durations indicate that the system require interleaving/deinterleaving structure to burst and correct the remaining burst using RS code. Such long fades are probably best handled by power control or adaptive modulation, leaving shorter fades and be bridged by interleaving and error correction.

The performance of the code for $t = 1$ to $t = 10$ for different link margins is evaluated using the following procedure.

The required value of $\left. \frac{E_b}{N_o} \right|_{required}$ for $P_{b_psk} = 10^{-6}$ and $M = 4$ (QPSK modulation) is:

$$\left. \frac{E_b}{N_o} \right|_{required} = \left(\frac{1}{2(\log_2 M)} \right) \left(\frac{Q^{-1}\left(\frac{P_{b_psk}}{2}\right)}{\sin\left(\frac{\pi}{M}\right)} \right)^2 = 11 dB \quad \text{Eq (4.45)}$$

If the relative received signal strength (RRSL) goes below the operating threshold (which corresponds to $\left. \frac{E_b}{N_o} \right|_{required}$), then the probability of bit error will increase i.e.

$$\frac{E_b}{N_o}(i) = \left. \frac{E_b}{N_o} \right|_{required} + E(i) \quad \text{Eq (4.46)}$$

Where i is the discrete level of the received signal strength and ranges from 1 to 30 in steps of

1. And $E(i)$ is the change of 1dB in the received signal strength for i discrete levels. From our observation of signal profile (in chapter 3), the relative received signal strength varies from 5dB above the mean to 35dB below the mean for majority of links. Therefore, $E(i) = 6 - i$ dB, and ranges between 5dB to -24dB relative to the mean.

The probability of error $P_4(i)$ for QPSK at each discrete level is then calculated as:

$$P_4(i) = 2Q\left(\sqrt{2\frac{E_b}{N_o}(i)}\right) \left(\text{prob}\left(\frac{E_b}{N_o}(i)\right) \text{ is in the discrete level } i\right) \quad \text{Eq (4.47)}$$

For each discrete level the probability of symbol error for RS code is then calculated as:

$$P_{b_RS}(i) = \frac{1}{n} \sum_{j=t+1}^n j \binom{n}{j} (P_4(i))^j (1 - P_4(i))^{n-j} \quad \text{Eq (4.48)}$$

Where $n = 2^8 - 1 = 255$

$k = 53$ bytes (one ATM cell)

$t = 0$ to 10 symbols

The result of the Eq (4-48) for different values of link margin is shown in figure 4-15. If QPSK modulation scheme is used with an average error probability of 10^{-6} then a link margin of approximately 10dB is required for $t = 10$ symbols.

Figure 4-15: Performance of RS-code at different link margin

4.2.5.2 Convolutional Codes

Convolution codes are very popular because of its simple hardware implementation. A commonly used convolutional code has:

$$\text{Constraint length} = 7 \text{ (Industry standard)}$$

Eq (4.49)

Since we require to have BER of 10^{-6} at the decoder, we can find the rate of the code by using following expression.

$$P_b < \sum_{d=d_{free}}^{\infty} \beta_d P_2(d) \quad \text{Eq (4.50)}$$

where $\beta_d =$ Coefficients in the expansion of the transfer function $T(D, N)$ defined at $N = 1$.

$$P_2(d) < [4p(1-p)]^{d/2}$$

If we define 10^{-6} for $P_2(d)$ then required free distance of the code should be $d_{free} > 5$. Using the following expression[45]

$$d_{free} < \min_{l \geq 1} \left\lceil \frac{2^{l-1}}{2^l - 1} (K + l - 1)n \right\rceil \quad \text{Eq (4.51)}$$

It is found that n should be equal to or greater than 2. This means that code rate is less or equal to 0.5. As we want to keep code rate as high as possible therefore following parameters of the code may give an optimum performance.

Constraint Length $K = 7$

$$\text{Rate } R = \frac{1}{2}$$

$$d_{free} = 10$$

The function Generator Matrix in octal form $\begin{cases} G_1 = 133 \\ G_2 = 171 \end{cases}$

This code is designed for hard decision decoding. Using soft decision decoding we can have a coding gain of 3dB in the performance of all codes.

The performance of the convolutional codes for different link margins are evaluated using the same procedure as for RS code, i.e:

$$P_b(i) \leq \frac{dT(D, N)}{dN} \bigg|_{N=1, D=\sqrt{4P_4(i)(1-P_4(i))}} \quad \text{Eq (4.52)}$$

Where $P_4(i)$ is calculated using Eq(4-47), and $T(D, N)$ is the transfer function of the given code and can be approximated for the given parameters (rate-1/2 and K=7) as follows (refer to [45][28]):

$$P_b(i) \leq \frac{1}{2}(36(D(i))^{10} + 211(D(i))^{12} + 1404(D(i))^{14} + 11633(D(i))^{16} + \dots) \quad \text{Eq (4.53)}$$

The performance of the code is plotted in figure 4-16 for different link margin (section 4-1):

Figure 4-16: Performance of Punctured Convolutional codes at different link margin

4.2.6 Interleaver

The expected fade duration at the threshold of 25dB below the mean of 5-sec intervals is approximately 570 μ sec. The expected aggregate downstream data rate for a high speed network such as LMCS, is between 10-155Mb/s. For a data rate of 40Mb/s, a 570 μ sec fade duration at 29.5GHz may corrupt 23kbits or 54 ATM cells. Burst error correcting codes for such a long fade are extremely complex and impractical. Interleavers, which randomize the burst errors, are usually used after the channel encoder. However, for high speed networks, the use of an interleaver may result in impractical memory size for data traffic, and unrealizable end-to-end delay for delay constrained traffic. The use of interleaver however does not affect the spectral efficiency of the communication system.

Though the use of very large interleavers for high speed network may be problematic, its performance is studied for periodic block and convolutional interleaver with and without Reed Solomon coding for different error correcting capability. The following parameters are used for the performance study of block and convolutional interleaver.

Periodic Block Interleaver

The choice of parameters for periodic block interleaver, should be as follows:

- Length of error burst $b \leq$ Number of Columns C of block interleaver
- Packet size (with or without coding) $p \leq$ Number of rows R of block interleaver

This implies a code that corrects a single error:

$$C \geq E\{FD\} \quad \text{Eq (4.54)}$$

Where FD is the 99th percentile of the fade duration statistics.

$$C \geq 23 \text{ kbits} \quad \text{At the data rate of 40 Mb/s} \quad \text{Eq (4.55)}$$

and, $R \geq N$ multiple of ATM cell

$$R \geq 424 N \text{ bits} \quad \text{Eq (4.56)}$$

where N is an integer.

If a Reed Solomon code with error correcting capability of t symbols is used, then the choice of the parameters C for block interleaver will change to:

$$C \geq \frac{E\{FD\}}{t} \quad \text{Eq (4.57)}$$

$$C \geq \frac{23 \text{ Kbits}}{t \text{ symbols}} \quad \text{Eq (4.58)}$$

Periodic Convolutional Interleaver

The convolutional interleaver has three parameters. The choice of parameters are as follows

- Length of Burst errors $b \leq$ Number of rows J of convolutional interleaver
- Length of packet size (with or without coding) = integer multiple $= JI$
- $I =$ length of shift register $= \frac{N}{J}$

The rest of the calculations are same as for block interleaver if used with RS code, for various error correction capability.

4.2.6.1 Performance Parameters for Interleaver

The performance of the Interleaver can be evaluated for the following parameters [48][40].

4.2.6.1.1 Efficiency

Efficiency[48] of the interleaver can be defined as the ratio of the length of the smallest burst of errors that can cause the error correcting capability of the code to be exceeded to the number of memory element used in the interleaver

For a block interleaver it is defined as [48]:

$$\gamma_{blk} = \frac{(Rt + 1)}{RC} \approx \frac{t}{C} \quad \text{Eq (4.59)}$$

And for convolutional interleaver it is defined as [48]:

$$\gamma_{con} = \frac{JI(t-1) + t}{\frac{J(J-1)D}{2}} = \frac{2t}{J-1} \quad \text{Eq (4.60)}$$

4.2.6.1.2 End-to-End Delay

End-to-End delay of the interleaver is defined as the time to interleave and deinterleave the sequence of data.

For a Block interleaver it is defined as:

$$\tau_{blk} = 2RC_{sec} \quad \text{Eq (4.61)}$$

And for convolutional interleaver:

$$\tau_{con} = N(J-1) \quad \text{Eq (4.62)}$$

4.2.6.1.3 Memory Requirement

The memory requirement is defined as the amount of memory required to store the permuted sequence prior to transmission plus the amount of memory required to store the sequence on the receiving end before decoding.

For block interleaver the amount of memory required is:

$$\Omega_{blk} = RC \text{ in both interleaver and deinterleaver} \quad \text{Eq (4.63)}$$

While for convolutional interleaver the amount of memory required is:

$$\Omega_{con} = \frac{N(J-1)}{2} \text{ in both interleaver and deinterleaver} \quad \text{Eq (4.64)}$$

The performance of the two interleavers has been evaluated using following parameters for various error correction capability of RS codes.

- The interleaving length for both interleavers is:

$$C = J = \frac{600 \times 10^{-6} \times 40 \times 10^6}{t \times 8} \text{ bytes} \quad \text{Eq (4.65)}$$

- Data rate = 40Mb/s.

Figures 4.17 and 4.18 show that the performance curve for the efficiency and end-to-end delay of the interleavers. These curve are calculated using Eq(4.59) to Eq(4.62) and table 4-1.

Figure 4-17: Randomization Efficiency of the Interleaver

Figure 4-18: End-to-end Delay of the Interleaver

4.2.7 Automatic Repeat Request (ARQ)

Automatic Repeat Request (ARQ) schemes are used to reduce the cell loss ratio, thereby ensuring reliable communication. Since most error control codes have better error detection capability than error correction, for reliable delivery of the data, ARQ can be used along with forward error correction schemes. That is, the corrupted packets which can't be corrected by forward error correction schemes will be recovered through retransmission request. ARQ schemes require feedback from receiver to transmitter, but are often necessary for reliable communications.

There are three basic types of ARQ schemes, namely, Stop-and-wait, Go-Back-N and Selective Repeat. Stop-and-Wait and Go-Back-N use a time-out counter before retransmission, whereas Selective-Repeat employs both time-out counter and NAK (negative acknowledgment) for retransmissions. Since the Stop-and-Wait protocol has lowest efficiency at low bit error rate, in this section throughput of Go-Back-N and selective repeat protocols are treated in more detail. The behavior of the above ARQ schemes is different for bursty error channel.

In the following sections design parameters and throughput of Go-Back-N and Selective Repeat protocols are examined for the fading statistics given in chapter 3 using procedure described in [22].

4.2.7.1 Throughput Estimation[22]

Link efficiency of ARQ schemes depend on:

- Channel bit error rate,
- Round trip delay T_d and
- Time-out period T_{out}

The round trip delay includes the propagation delay in both directions, transmission time of the acknowledgment and the processing delay of received block, i.e:

$$T_d = 2T_{pg} + T_{pr} + T_{aix} \quad \text{Eq (4.66)}$$

where, T_{pg} = Propagation Delay

T_{pr} = Processing Delay

T_{aix} = Transmission Time of the acknowledgement

4.2.7.1.1 Assumptions

The following assumptions are made to design and examine the ARQ schemes for DAVIC 1.2 recommendations.

- Upstream data rate is 10Mbps .
- Link Rate in the downlink is 40Mbps
- Frame Length 3msec (DAVIC Recommendation [57])
- Probability that a user has a allocated time slot is 1.
- Time Slot is equal to one RS coded (68,53,5) ATM cell.
- Cell Radius $D = 2km$

At 2km the Propagation delay is:

$$T_p = \frac{2 \times 10^3}{2 \times 10^8} = 10 \mu \text{ sec} \quad \text{Eq (4.67)}$$

The transmission time of the acknowledgment is

$$T_{air} = \frac{544}{10 \times 10^6} = 54.4 \mu \text{sec} \quad \text{Eq (4.68)}$$

Since the frame size is 3msec long hence the maximum round trip delay is 3msec approximately (ignoring the processing times) while the minimum round trip delay will be:

$$T_d = 20\mu\text{sec} + 54.4\mu\text{sec} = 74.4\mu\text{sec} \quad \text{Eq (4.69)}$$

The size of a time slot in the downstream direction is 204 bytes. Therefore at 40Mbps the transmission delay of one TS is $40.8\mu\text{sec}$ which corresponds to a round trip delay of 2 TS (of 204 bytes), i.e:

$$T_d = 2TS \quad \text{Eq (4.70)}$$

It is recommended that the time-out counter should be at least twice the round-trip delay, i.e.,

$$T_{out} \geq 2(2T_{pg} + T_{pr} + T_{air}) \quad \text{Eq (4.71)}$$

$$T_{out} \approx 148.8\mu\text{sec} \approx 4TS \quad \text{Eq (4.72)}$$

A modulo m counter is used for time-out, and the maximum number of packets transmitted before waiting for acknowledgment is $m-1$. If acknowledgment is not received then the time-out expires and retransmission will start after the last acknowledged packet. Since $T_{out} = 4TS$ is not possible with 2 bits, a 3 bit counter will be used. Hence with 3 bits we will have:

$$T_{out} = 7TS \quad \text{Eq (4.73)}$$

4.2.7.1.2 Performance Evaluation

The probability that the transmission is successful is the probability of successful transmission during an interfade duration[22]:

$$P_{succ} = P(RRS(L > RRS_{min}))P(IFD > TSD) \quad \text{Eq (4.74)}$$

where IFD = 99th percentile of Inter-fade duration

$RRSL$ = Relative received Signal strength

TSD = Duration of Time slot = $40.8\mu\text{sec}$

The second factor in Eq(4.74) is the probability that the entire block is transmitted during an interfade duration. The probability that one transmission is required to transmit the frame successfully is [22]:

$$P_{SA}(rt=1) = P_{succ}P_{ch}Pr(FD_r < (T_{Fr}(T_d - 1))) \quad \text{Eq (4.75)}$$

where P_{ch} = Channel Block Error Rate

T_{Fr} = Frame Duration (secs)

FD_r = Fade Duration in the return channel

rt = retransmission number

For $rt \geq 2$, the probability that rt attempts are required for successful transmission is

$$P_{SA}(rt \geq 2) = (P_{succ})^2 P_{ch} (Pr(T_{Fr}(T_d + T_{out}(rt-1))ms < FD_r < T_{Fr}(T_d + T_{out} rt)ms)) \quad \text{Eq (4.76)}$$

Hence the probability of successful transmission of the frame in rt attempts will be:

$$P_{STr}(rt=1) = P(P_{succ})^2 + P_{SA}(rt)_{rt=1}$$

$$P_{STr}(rt \geq 2) = P_{SA}(rt) + \sum_{i=1} P_{ch} P_{SA}(rt-i) Pr(T_{Fr}(T_{out}(i-1))ms < FD_f < T_{Fr}(T_{out} \times i)ms) \quad \text{Eq (4.77)}$$

The average number of transmissions required is:

$$N_T > \sum_{rt=1}^{\infty} (rt) P_{STr}(rt) \quad \text{Eq (4.78)}$$

Hence the throughput of Go-Back-N will be greater than the reciprocal of N_T :

$$\eta_{GBN} > \frac{1}{N_T} \quad \text{Eq (4.79)}$$

The calculation of throughput for Selective-Repeat is quite complex because the retransmis-

sion can be performed before time-out period on the reception of NAK (negative acknowledgment). However, a transmission would be successful if two way transmission are successful. Therefore, a simple approximation of throughput is:

$$\eta_{SR} = \left(P(RRSL > LinkMargin) \left(\frac{IFD - TSD}{IFD} \right) \right)^2 \quad \text{Eq (4.80)}$$

Throughput of Go-Back-N and Selective-repeat protocols at different link margins using the above equations, table 4-1 and the results given in chapter 3 are shown below.

Figure 4-19: Link utilization of the ARQ Schemes for Burst Errors

4.3 PERFORMANCE EVALUATION OF DAVIC 1.2 RECOMMENDATIONS FOR LMCS

Digital Audio Visual Council (DAVIC) is a non-profit organization for promoting standards for multi-media communication technology. One of its many recommendations include the Recommendations for LMCS/LMDS systems. In this section we have studied the performance of DAVIC 1.2 physical layer specifications [11] for LMCS. The performance is evaluated for G.826 [34] physical layer performance parameters as described in below.

4.3.1 Physical Layer Specifications

Two approaches have been recommended for the downstream transmission in the DAVIC 1.2 Physical layer specifications. These are described below:

Downstream Scenario 1:

- Outer RS code with $n = 204$ bytes, $k=188$ bytes (187 bytes of information and 1 byte for synchronization) and $t = 8$ bytes.
- Convolution Interleaver with a depth of 12 bytes and code word length of 204 bytes.
- Punctured convolutional code with constraint length equal to 7 and mother code rate of $1/2$.
- QPSK with Gray coding scheme.

Downstream Scenario 2:

- RS code with $n = 204$ bytes, $k=188$ bytes (187 bytes of information and 1 byte for synchronization) and $t = 8$ bytes.
- Convolution Interleaver with a depth of 12 bytes and code word length of 204 bytes.
- 16-QAM with Gray coding scheme.

Upstream:

- RS code with $n = 63$ bytes, $k=53$ bytes (187 bytes of information and 1 byte for synchronization) and $t = 5$ bytes.
- QPSK with Gray coding scheme.

4.3.1.1 Procedure

Following procedure was used to determine the performance of DAVIC 1.2 physical layer specifications.

We assume the maximum and minimum received signal strength in the downstream direction are:

$$RSL_{max} = -30\text{dBm} = -60\text{dBW}$$

$$RSL_{min} = -60\text{dBm} = -90\text{dBW}$$

Eq (4.81)

If an antenna gain of 30dB is assumed then the received signal strength before the antenna will be:

$$\begin{aligned} RSL_{max} &= -30\text{dBm} + 30\text{dBi} = 0\text{dBm} = -30\text{dBW} \\ RSL_{min} &= -60\text{dBm} + 30\text{dBi} = -30\text{dBm} = -60\text{dBW} \end{aligned} \quad \text{Eq (4.82)}$$

If bandwidth BW of the system is 40MHz, noise figure Nf is 1.5 (2dB) and temperature is $300^\circ K$ thence noise N is:

$$N = K(BW)TNf = 2.5 \times 10^{-13} = -126\text{dB} \quad \text{Eq (4.83)}$$

where K = Boltzman Constant . Hence the maximum and minimum Signal to noise ratio is:

$$\begin{aligned} \frac{S}{N_{max}} &= -30 - (-126) = 96\text{dB} \\ \frac{S}{N_{min}} &= -60 - (-126) = 66\text{dB} \end{aligned} \quad \text{Eq (4.84)}$$

And the corresponding $\frac{E_b}{N}$ values are

$$\begin{aligned} \frac{E_b}{N_{max}} &= \frac{1}{k} \left(\frac{S}{N_{max}} \right) \\ \frac{E_b}{N_{min}} &= \frac{1}{k} \left(\frac{S}{N_{min}} \right) \end{aligned} \quad \text{Eq (4.85)}$$

where k = Number of bits in the Constellation . which is equal to 2 for QPSK:

$$\frac{E_b}{N_{max}} = 93\text{dB}$$

$$\frac{E_b}{N_{min}} = 63\text{dB}$$

Eq (4.86)

This shows that the recommended margin against fading is on the order of 45 to 75dB. In real situation it will be good enough to maintain the quality of service and G.826 EPOs. Beside this fact, in order to see the performance of DAVIC recommendations, we assume that the received strength is near the noise floor and then increase power in steps of 3dB to observe the required link margin for G.826 recommended EPOs. For this purpose we calculated the probability density function of the received signal strength from the results given in previous chapter as shown in figure below:

Figure 4-20: *Probability Density Function of Received Signal Strength*

The average error probability is then calculated as follows:

$$\overline{P_e} = \sum_{i=1}^{21} Pr(Thr(i) \leq RSSL \leq Thr(i+1)) P_M(i) \quad \text{Eq (4.87)}$$

where $Thr(i)$ is the threshold define from -51dB to 3dB in steps of 3 (for example, $i = 1$ corresponds to threshold of -51dB, $i = 2$ correspond to threshold level of -48dB and so on) and $P_M(i)$ is the probability of error for QPSK/16-QAM at that threshold. Then the probability of error P_e using RS code and convolutional is calculated using Eq(4-43) and Eq(4-53). Using these error probability maximum number of blocks in error are calculated as;

$$EB_{max} \leq (\text{Data Rate}) P_e \quad \text{Eq (4.88)}$$

Error second ratio is then calculated as follows (by definition)

$$\begin{aligned} ESR &= 1 & \text{if } EB \geq 1 \\ ESR &= EB & \text{if } EB < 1 \end{aligned} \quad \text{Eq (4.89)}$$

If 30% or more block are in error in one second than that duration is declared as a *SES*.

4.3.1.2 Performance Results

The performance results for DAVIC downstream scenario 1 are shown in figures 4-21 and 4-22. In this scenario, maximum link margin of 4 dB is required to achieve BER of 10^{-20} (approximately). For the same link margin, ESR is in the range of 10^{-7} to 10^{-22} at the data rate 40 Mbps. The performance results for scenario 2 are shown in figures 4-23 and 4-24 it can be observed that a link margin of 17 dB is required to achieve BER of 10^{-20} . However, for a link margin of 4 dB BER is 10^{-4} and ESR is 10^{-3} at a data rate of 40 Mbps. Scenario 1 one appears better for narrowband LMCS channel. For the upstream scenario performance curves are shown in figure 4-25 and 4-26. It can be observed that link margin of 6 dB is required to achieve BER of 10^{-6} and ESR of 10^{-11} at a data rate of 10 Mbps.

Figure 4-21: BER performance for DAVIC downstream Scenario 1

Figure 4-22: ESR performance for DAVIC downstream Scenario 1

Figure 4-23: BER performance for DAVIC downstream Scenario 2

Figure 4-24: ESR performance for DAVIC downstream Scenario 2

Figure 4-25: BER performance for DAVIC upstream

Figure 4-26: ESR performance for DAVIC upstream

4.4 SUMMARY OF THE RESULTS

In this chapter, we discussed various system design issues for LMCS channel. We suggest three different power control algorithms to adapt the power of the user according to the channel condition to overcome fading. The first algorithm is based on the periodic scanning of the channel, second algorithm is based on the retransmission request (ARQ) from the user, and third approach based on the computation of BER of each packet. Though the scanning overhead in first algorithm is much more than the other two, its lot more simple than the other two algorithms.

Since increase in power to overcome fading can result in severe interference we also suggest use adaptive constellation size of the modulation scheme to adapt the temporal variation of the

LMCS channel. In this respect we evaluate the performance of the MPSK and MQAM for three different scenarios. It has been shown that both error performance and spectral efficiency can be improved through the use of adaptive modulation scheme without the risk of interference.

The parameters of Reed Solomon and Convolutional codes are also suggested for temporal variation of LMCS channel. Though the use of interleaver for high speed network results in impractical memory size, the performance of block and convolutional interleavers were evaluated. It has been found that practical implementation of interleaver requires link margin of more than 35dB.

The throughput of selective-repeat and go-back-N is also estimated for LMCS channel. It has been observed that the throughput of selective-repeat ARQ increase sharply after the link margin 5dB, while the throughput of go-back-N increases exponentially after the link margin of 25dB.

The performance of DAVIC1.2 recommendations were also evaluated for both upstream and downstream scenarios for G.826 EPO. The performance curves shown in this section does not include the margin for rain attenuation and interference etc. This results in outstanding performance of DAVIC1.2 recommendations.

Conclusions and Suggestions

5.1 SUMMARY OF THESIS

The main objective of this study was to find optimum design parameters for LMCS system based on the actual temporal variations statistics.

For this purpose we measured the temporal variations of a narrowband system of 4MHz at a carrier frequency of 29.5 GHz. The temporal variations that we studied were mainly caused by moving foliage or vehicular traffic which may be more in the nature of time-varying shadowing rather than time-varying multi-path. Moreover, the use of highly directive antennas at the subscribers will further reduce the effects of multipath. The effects of time variations due to shadowing will be the same for broader bandwidth systems. Therefore, these measurements are reasonably representative of broader bandwidth and can be used for optimum and cost effective LMCS solutions.

With the help of these measurements, we studied the following:

- Adaptive Modulation Schemes.
- Popular FEC Schemes.
- Requirements of Interleaver.
- Evaluation of ARQ Schemes.
- Power Control Schemes.
- Performance evaluation of DAVIC physical layer recommendations for G.828 EPOs.

5.2 SUMMARY OF RESULTS:

A number of issues were studied as described in the earlier section. A brief summary of all these investigations are described here.

Field measurements were performed in and around Carleton university during the Fall of 1998 to investigate the temporal variations due to foliage or moving vehicles. The measurement results show that the maximum fade depth for foliage is 40dB and for vehicular traffic is 50dB, with average probability of 10^{-6} . The 90th percentile of fading of 3dB and 9dB bandwidth was noted to be; 14Hz and 41Hz for foliage movement while 20Hz and 42Hz for vehicular traffic respectively. The 99th percentile of fade rate at 30dB below the mean is approximately zero fades/sec for foliage and 15fades/sec for vehicular traffic. Also the 99th percentile of fade and

non-fade duration at 30dB threshold are; approximately zero second and 4sec for foliage movement whereas 0.1sec and 3.8sec for vehicular traffic respectively. It is important to note that the fading statistics are different for vehicular traffic and foliage movement.

Kolmogrov-Smirnov tests were performed to find the closeness of fit of the CDF of the acquired data with popular wireless channel fading distributions. It was observed that for foliage 81%, 95%, 1% and 16% CDF of the acquired data passed for Rayleigh, Ricean, Lognormal and Nakagami respectively. While for vehicular traffic 42%, 40%, 0.1% and 3.3% passed for Rayleigh, Ricean, Lognormal and Nakagami respectively.

Three power control algorithms namely: Periodic Power Control, ARQ Based Power Control and BER Based Power Control, are suggested. Periodic power control algorithm is the simplest of all other schemes, however requires frequent control messages which consumes more bandwidth.

Performance of adaptive constellation size of PSK and QAM were evaluated. It was found that QAM gives better spectral efficiency and requires fewer constellation levels than PSK. The two adaptive modulation schemes perform better than the ordinary QPSK but require complex transceivers and have high response-time (in order to switch from one constellation to the other).

The performance for Reed Solomon code and Rate Punctured code is also evaluated. The performance of convolution interleavers and block interleavers were compared with the available channel statistics. The end-to-end delay at a data rate of 40Mbps with RS-code having error

correction capability of 2 bytes using convolution interleaver is 40msec and using block interleaver is 80 msec. While the randomization efficiency for similar parameters is 14.2% for block interleaver and 64% for convolution interleaver.

The performance of Stop-and-Wait, Go-Back-N and Selective-Repeat ARQ schemes were compared. Go-Back-N has better performance at low BER but Stop-and-Wait outperforms the former for BER of less than 10^{-3} . Selective-Repeat gives the best performance among the mentioned ARQ schemes, however has the more complex implementation.

5.3 SUGGESTIONS FOR FUTURE RESEARCH

In order to complement our study the following further work is suggested:

- Investigations of temporal variations of broadband channel.
- Performance evaluation of the Turbo Codes using the results of temporal various for data traffic.
- Simulation study of adaptive modulation schemes.
- Simulation study of the power control schemes.

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